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DEPRESSIONS OF THE NORTHERN PORTION OF THE SOUTHERN HIGH PLAINS, EASTERN NEW MEXICO. By Sheldon Judson

VOLCANIC GEOLOGY OF TOOWA VALLEY, SOUTHERN SIERRA NEVADA, CALIFORNIA. By Robert W. Webb

ORE MINERALIZATION IN THE HOMESTAKE GOLD MINE, LEAD, SOUTH DAKOTA. By James A. Noble

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LATE CENOZOIC BLOCK FAULTING IN WESTERN MONTANA. By J. T. Pardee

STRATIGRAPHY AND STRUCTURE OF THE MT. PAWTUCKAWAY QUADRANGLE, SOUTHEASTERN NEW HAMPSHIRE. By Jacob Freedman

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NEW PROJECT GRANTS

J. Harlan Johnson, F.G.S.A., will study types of fossil coralline algae in museums abroad

Kazuo Kuroda will study the distribution of fluorine and chlorine in igneous rocks

J. Laurence Kulp, M.G.S.A., will establish a Strontium Isotope Method to measure age of sedimentary and metamorphic rocks

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
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PEDIMENT CONCEPT APPLIED TO SHINARUMP AND SIMILAR CONGLOMERATES

BY WM. LEE STOKES

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ABSTRACT

The Shinarump and Buckhorn conglomerates and the Dakota sandstone are widespread deposits of Mesozoic age in the western interior. The physical characters indicate a fluvial origin, but the wide areal extent, scarcity of fossils, and exceptional thinness are difficult to explain by current concepts. It is suggested that these and similar continental formations are extensive pediment deposits which originated by processes observable in present-day arid and semiarid regions. These ancient deposits are compared with known pediment deposits, and the implications with regard to stratigraphic terminology and age assignments are briefly discussed.

INTRODUCTION

Ever since the first scientific explorations of the West certain thin but widespread conglomerates have excited the interest of stratigraphers. The physical features of these formations have been described and discussed by many writers, and numerous measured sections have been published, but as yet no satisfactory and comprehensive analysis of their genesis has been made. The present paper concerns the manner of formation of three conglomerates: the Shinarump and equivalents of Triassic age, the Buckhorn and equivalents of probable early Cretaceous age, and the Dakota of probable late Cretaceous age.

SHINARUMP CONGLOMERATE

The Shinarump conglomerate and recognized equivalents outcrop over wide areas in northern Arizona and southern Utah and less extensively in central, northern, and western Utah, western Colorado, northwestern New Mexico, southeastern Nevada, and southwestern Idaho. Its total original areal extent exceeded 125,000 square miles. It is usually less than 50 feet thick but may locally reach 300 feet. At a few places, especially near the edges, the Shinarump becomes a mere scattering of pebbles or coarse sand. The lithology is not uniform; there are large areas of sandstone and, even where conglomerate is conspicuous, there are usually lenses of shale, siltstone, and lime pellets.

The lower contact is almost everywhere an erosional unconformity, and at a few places, especially in the salt-dome region of eastern Utah, angular discordances are evident. The upper contact is not so well marked, as the Shinarump grades into the overlying beds. The typical Shinarump, between the comparatively nonresistant Moenkopi and Chinle formations, crops out as a conspicuous cliff overlying and protecting the Moenkopi and providing a stripped surface above which the Chinle rises.

One of the most striking features is the abundance of petrified wood which occurs not only as large logs, but also as rounded pebbles and cobbles. Practically all the rounded fragments of wood appear to have been silicified before final deposition, suggesting that they may have been buried as logs in the Shinarump, been petrified, and later exhumed and broken

up before reburial in the same formation at another locality.

A few other fossils include cycads, miscellaneous and nondiagnostic fragments of phytosaur and amphibian bones, and fresh-water mollusks. None of these gives an accurate age determination for the formation, and it is currently designated as questionably late Triassic. Some interesting observations have been made regarding the derived fossils found in the chert pebbles of the conglomerates. McKee (1936) reports that they are of marine organisms, some of which are diagnostic brachiopods which originated in the Kaibab formation. He deduces that, for northern Arizona at least, much of the Shinarump was derived from highlands to the south and southwest. The writer has also found specimens of late Paleozoic invertebrates in the cherts of the Shinarump.

Other constituents of the formation are not so easily determined. Gregory, who has probably examined more outcrops of Shinarump than any other geologist, has discussed this problem in many of his papers. In his report on the San Juan area he has written (1938):

"The unsolved problem of Shinarump lithology is the source of the pebbles of the conglomerate. The slabs of sandstone and clay balls may have come from underlying beds, the cycads doubtless grew where their fossils are found and the petrified trees are probably driftwood. Some of the limestone fragments may represent a once much thicker Moenkopi. . . . But no Triassic or Carboniferous formation so far mapped includes material that might supply the varicolored quartz and quartzite. The quartzites differ in no essential from those in the pre-Cambrian of Utah and Arizona."

As suggested by these observations there were areas of Precambrian quartzite as well as late Paleozoic rocks exposed in central Arizona in Shinarump time. Igneous rocks are rare in the southern and southwestern outcrops but constitute a large part of the material in northern and eastern facies. The fragments are usually resistant pebbles of quartz, but much of the finer material is reported to be decomposed feldspar. In the Uinta Mountains the formation is described as a feldspathic grit with larger pieces of quartz. This crystalline material was probably derived from the Ancestral or Colorado Rockies, especially the Uncompahgre unit, the core of which was exposed at this time in western Colorado and eastern Utah.

All evidence therefore indicates that the conglomerates of the Shinarump, especially those more resistant types near the base, were derived not from underlying rocks but from various highland areas surrounding the area of deposition. Some of the material found over most of the southern and southwestern outcrops is of sedimentary origin, while igneous and metamorphic types are more common in the north and northeastern part of the area. Many of the fragments must have been transported hundreds of miles to their present locations. This was probably accomplished in intermittent stages with much reworking of material and consequent abrasion of the rock fragments.

Buckhorn Conglomerate

Much that has been said regarding the Shinarump is applicable to the Buckhorn conglomerate and its equivalents. The writer proposed the name Buckhorn (1944, p. 966) for a persistent conglomeratic bed overlying the Morrison formation in the San Rafael Swell and adjacent areas in Utah. It is not so prominent or well marked as the Shinarump and has received correspondingly less attention. Its equivalents as interpreted by the writer are the lower conglomerate of the so-called Dakota group of the Front Range in Colorado (the Saurian conglomerate of the dinosaur collectors), the lower conglomerate of the Post-McElmo beds of western Colorado, the Cloverly conglomerate of much of Wyoming, the Dakota sandstone of the Inyan Kara group of eastern Wyoming, the so-called "quartz-crystal" sandstones and associated conglomerates of central Wyoming, the basal member of the Purgatoire group of southeastern Colorado and near-by territory, the conglomerate at the base of the Kootenai in the vicinity of Cut Bank, Montana, and equivalent conglomerates within the so-called Kootenai of more southeasterly parts of Montana. In Canada the conglomerate at the base of the Lower Blairmore is also thought to be equivalent.

In all but the more northern localities the conglomerates lie above undoubted Morrison and below variegated beds thought to be of early Cretaceous age. Fossil evidence is nonconclusive, and much more field work is needed to establish the physical continuity and time

equivalence of the various units. In spite of the lack of definite detailed evidence as to age, widespread gravel sheets, even more extensive than the Shinarump, were formed in post-Morrison and pre-late Cretaceous time in the Colorado Plateau and Rocky Mountain area. These conglomerates seldom exceed 50 feet in thickness and may be represented locally by only scattered pebbles or coarse sand. Fluvial origin is indicated by the type of bedding, the nature of such fossils as are found, and the general paleogeographical location.

Disarticulated and fragmentary dinosaur bones and petrified logs are rather common, and some of the finer deposits contain poorly preserved mollusk shells. Derived fossils from the chert pebbles of the conglomerate studied by the writer include representatives of at least five invertebrate phyla; among these are specimens of diagnostic fusulinid genera that permit close age assignment for the source rocks. The evidence indicates that late Paleozoic sedimentary beds, mostly Permian and Pennsylvanian, were undergoing erosion in Buckhorn time and were supplying detritus over wide areas. Some of the pebbles must have traveled over 500 miles to their present localities. All the fragments are well rounded, show numerous percussion marks, and otherwise indicate much wear and long transportation. The most abundant material is chert; quartzite is next in importance. Igneous rocks are extremely rare.

The problem of dating the Buckhorn conglomerate and its equivalents is as difficult as dating the Shinarump. The time lapse which must be accounted for is long—sufficient to permit the accumulation of very thick sedimentary deposits in the Gulf Coast area. Beds below the conglomerate contain the large dinosaur quarries and are quite definitely Jurassic. Beds above are mostly barren of diagnostic fossils, but most are thought to be early Cretaceous. Again the most perplexing question is whether or not the unconformity at the base of the conglomerate alone accounts for the lost time interval. If it does the gravel sheet should logically be assigned to the early part of the period to which the succeeding beds belong.

Dakota Sandstone

Remarks concerning this formation apply only to the facies exposed in the Colorado Plateau and the Rockies and not to the formation as known in the more central portions of the continent. In the area under discussion, the formation has usually been designated as questionable Dakota indicating some doubt as to its equivalence with the true Dakota at and near the type section. Where the Dakota and Buckhorn are both present they are usually separated only by a sequence of beds less than 300 feet thick. So close is the topographic and stratigraphic relationship that in many cases the two have been included in the same group or even formation. Usually this sequence presents a typical threefold aspect with the Buckhorn or equivalents below, a middle varicolored shale unit, and the upper so-called Dakota. The whole assemblage is a persistent ridge- and hogback-maker.

In spite of the close superficial relationship of the Dakota and Buckhorn the time involved within and between these formations is long, including some of the Jurassic, all of the early Cretaceous, and part of the late Cretaceous. It has been convenient for cartographic and descriptive purposes to regard the unconformity at the base of the Dakota as representing all or most of the time lapse, and on this theory rocks of lower Cretaceous age usually have been assumed to be absent in the Colorado Plateau. Evidence is accumulating to show that a thin sequence of this age is probably present.

Overlying the Dakota is the Mancos shale or its equivalents, with marine faunas whose late Cretaceous age is well established.

The Dakota includes conglomerate, coal, sandstone, shale, and quartzite irregularly interfingering and alternating with each other. The type of bedding, the fossils, and the paleogeography all indicate a dominantly fluvial origin. The carbonaceous beds are assumed to have accumulated in lakes and swamps.

The formation ranges from a knife edge of scattered pebbles to 200 feet in thickness and averages 20 to 30 feet.

The rock fragments of the conglomerate consist of sandstone, quartzite, and chert. In general the rocks are not so durable as those of the Buckhorn. In central Utah, gray, buff, and yellow sandstone and quartzite predominate with chert present in minor amounts. Eastward the quartzite and sandstone fragments become

smaller and less numerous, and the chert increases correspondingly in importance.

No fossils were found in the quartzite and sandstone pebbles, but their lithology is very similar to that of the Oquirrh formation of Pennsylvanian and Permian age. Since the pebbles are not strongly colored or banded it is assumed that they were not derived from Precambrian rocks of the Uinta Mountains. There can be little doubt that the Dakota was derived from the west and southwest and that the material comprising it was eroded mainly from late Paleozoic sedimentary rocks.

Summary of Physical Characters

The chief characteristics of the conglomerates are:

(1) All are continental and fluvial in origin as indicated by their primary structure, their fossils, and their paleogeographical positions.

(2) All have a clearly marked erosional unconformity at the base, but in practically all places they grade into the overlying beds.

(3) All are exceptionally widespread for continental formations and are at the same time remarkably thin, averaging roughly 50 feet in thickness.

(4) The age of each is difficult to fix. Thus the Shinarump is either middle or late Triassic, the Buckhorn questionably lower Cretaceous, and the Dakota questionably upper Cretaceous.

(5) A long time lapse must be accounted for by the unconformity, or by the unconformity and the overlying conglomerate. For the Shinarump it is all of the middle Triassic, for the Buckhorn much of lower Cretaceous and some of the Jurassic, and for the Dakota some of the early Cretaceous and some of the late Cretaceous.

(6) The fossil evidence is weak or nondiagnostic. Petrified wood, broken bone fragments, and scattered fresh-water invertebrates, all of doubtful index value, constitute practically all the known organic remains.

(7) The rocks constituting the pebbles are mostly of the most durable sorts, mainly quartz, chert, and quartzite. The fossils indicate that some of these rocks were derived from sedimentary beds and have traveled long distances, in some cases hundreds of miles, to their present locations. Fragments of underlying beds are also present.

(8) The Shinarump and the Buckhorn are overlain by terrestrial beds; the Dakota is followed by the marine Mancos shale.

Opinions as to Origin

A few stratigraphers, especially those connected with the earlier surveys, have considered these conglomerates in one place of another as being marine. With few exceptions, however, recent workers have ascribed them to the work of streams, but few have amplified the idea. As to the origin of the Shinarump conglomerate and the underlying unconformity, Gregory (1931, p. 52) wrote:

> "After Moenkopi time there was widespread erosion, which partly beveled the soft Moenkopi strata and in places carved distinct erosion channels in them. The *subsequently* deposited Shinarump constitutes a very widespread thin veneer which covers this erosion surface and fills its depressions."

In his paper on the San Juan region Gregory (1938, p. 48) reports:

> "The top of the Moenkopi is an erosion surface over which is spread the Shinarump conglomerate. In the development of this surface parts of the Moenkopi, and perhaps higher beds not anywhere now represented, were removed from large areas of the plateau province. Erosion continued until both flat-lying beds and tilted beds were worn down to a surface of low relief that marked the end of a physiographic cycle. For beginning a succeeding cycle the conditions were suitable for the deposition of sheets of conglomerate (Shinarump)."

In a more recent paper Camp, Colbert, McKee, and Welles (1947) have written:

> "Everywhere the top of the Moenkopi formation is a surface of erosion. It is conspicuous where channels have been carved in the red shales or sandstones and subsequently filled with gravels of the Shinarump conglomerate."

These quotations indicate that the underlying unconformity has been regarded as having been produced as a distinct and separate episode accomplished in middle Triassic time, and the deposition of the Shinarump as a second independent episode of possibly late Triassic time. In other words, the cutting of the unconformity and the spreading of the gravel sheet were separated by a long time lapse. The Shinarump is usually assigned to the late Triassic and is

frequently referred to as a "basal conglomerate of the Chinle", "initial deposit of the Chinle", and "introductory phase of the following formation."

Similar quotations, deductions, and arguments could be given in connection with the Buckhorn and equivalents and the Dakota. W. T. Lee, who observed these beds over very extensive areas, believed the Dakota group to be a basal conglomerate laid down in advance of the late Cretaceous marine invasion (Lee, 1927). This was when the Morrison was considered Early Cretaceous and the time lapse involved was thought to be not so great as is now assumed. Lammers (1939) believes that the Cloverly conglomerate and its equivalents were the first deposits of Cretaceous age in the Rocky Mountains. He does not discuss specifically the manner of origin but regards these conglomerates as being the first expression in Rocky Mountain sediments of the uplift of the Sierra Nevada.

The implications of these concepts should be carefully analyzed. The vast plain of aggradation of pre-Shinarump time, according to current theories, was subjected to erosion for not less than several million years. Granting that recorded observations of the underlying unconformity are correct, erosion must have been essentially uniform throughout the area. Although the base level of the ocean was many miles away, there were few notable channels of consequent streams cut into the surface of the easily erodable Moenkopi formation. No recognizable soil profiles were developed on the supposedly long exposed surface, and the sediments immediately beneath the conglomerate are usually relatively fresh in appearance.

Current theories imply that, after widespread erosion, extensive gravel sheets were laid down, presumably by the same fluvial agents that had previously been engaged exclusively in eroding the surface. The gravel, spread with surprising uniformity over an exceedingly wide area, constituted after consolidation a basal conglomerate or introductory phase for the next higher formation into which it grades.

The difficulties involved in this paleogeographical reconstruction amply justify a reconsideration of the facts and revisions of current theories. Evidences of fluvial origin are abundant, but the postulated sequence of events is difficult to reconcile with what may be observed of present-day rivers and their deposits.

Review of the Pediment Concept

Brief mention must be made of pediments and the forces operating to produce them since it is the thesis of this discussion that conglomerates such as the Shinarump may be formed by the same processes of pedimentation that are operating in existing arid and semiarid regions.

Although it is admittedly an important factor in shaping present land surfaces, pedimentation has not heretofore been regarded as having operated to produce surfaces or deposits of ancient sedimentary terrains. A pediment is a smooth, sloping surface of erosion which bevels rocks of varied hardness and structure and is lightly veneered by debris derived from adjacent high areas undergoing erosion. Authorities do not agree as to whether the veneer of loose material is essential to the concept or the definition. Pediments are forming at present mainly in arid and semiarid regions and cover in the aggregate a sizable portion of the earth's crust.[1]

The following are prerequisites for their formation:

(1) Fluvial action, no matter how widely distributed in space or time, must be the dominant agent of rock erosion and transportation.

(2) There must be a relatively high-standing source of large quantities of coarse, durable detritus.

(3) The detritus must be loose, unconsolidated, and relatively free from vegetation so as to instantly satisfy the capacity of the temporary or permanent streams that are present.

Provided the foregoing conditions are met, pedimentation may be initiated at any time or

[1] Howard (1942) has restricted the term pediment to that portion of the surface that is cut in bedrock and has proposed the term *peripediment* for the continuation of the surface across skirting alluvium or earlier fill. The term *pediplane* he suggests to embrace both pediment and peripediment. *Pediplanation* is the process of formation of pediplanes. These terms appear to reflect valuable concepts but since they have not yet been generally evaluated and used by geomorphologists and textbook writers they have not been used in this paper.

place regardless of the stage of erosion previously attained, the type of topography, or whether the terrain has previously been undergoing aggradation or degradation. Present-day pediments are forming mainly in areas that have undergone extensive degradation, as the Colorado Plateau and the Great Basin. Isolated fault-block mountains and great retreating escarpments are being destroyed and reduced to level plains. In the Colorado Plateau the material is being carried away by the Colorado River, and in the Great Basin it is trapped in interior basins. As the process is observed in operation several effects are notable. Small islands of bedrock are erased, and retreating escarpments tend to remain relatively straight through the removal of projecting spurs and transverse ridges. This eating back of bedrock slopes and removal of small isolated remnants has been ascribed to the lateral planation of overloaded streams, to rill wash, and to backweathering of slopes (Bryan, 1935; Howard, 1942; Johnson, 1932). These are probably potent factors but do not fully explain the removal of material to an almost level plain concurrently with the production of sheets of coarse detritus. It is a well-recognized truth, embodied in the so-called Law of Differential Erosion, that areas of hard rock come to stand higher than areas of soft rock. As a logical corollary, the debris of the harder rocks must be transported across the areas of softer rocks during erosion. Any comparatively low-standing area may endure for a while, but it cannot compete indefinitely with the stream of resistant rock fragments which passes around its edges. The bedrock remnant cannot be protected or replaced; each particle removed is permanently lost. On the other hand, the stream of gravel is constantly replenished and will maintain, like water, an essentially uniform level. Ultimately bedrock patches disappear, and the gravel sheet of the pediment becomes continuous. As the loose detritus is reworked and transported in slow stages the underlying beds are locally and temporarily eroded so that general uniformity of grade and topography is maintained, not only on the gravel sheet, but on the bedrock surface below as well.

Application to Ancient Continental Deposits

Comparison of known pediments and ancient deposits and surfaces suspected of having been produced by pedimentation is now possible. Modern pediments at the time of formation have an underlying bedrock surface of erosion remarkably smooth in general aspect but which shows small-scale channeling. This surface may be cut across tilted or horizontal beds and shows little or no variation as it transects hard and soft layers alike. The bedrock surface shows little or no weathering, and soil profiles have evidently had no opportunity to form. However, ground water travelling along the gravel-bedrock contact may accomplish some leaching effects that may be mistaken for surface weathering.

The gravel sheet of a typical pediment is usually rather thin, averaging 10 to 40 feet thick. The constituent pebbles are of the most durable sorts available in the source areas. Away from the source the fragments of less durable materials become smaller and eventually disappear, and the more durable materials increase correspondingly in importance.

The gradient of present-day pediments varies as determined by delicate and complex relationships among the factors of distribution and quantity of runoff, quantity of debris, size of fragments, and the speed with which these fragments are reduced in size. When all these factors are constant or stabilized the gradient is also stabilized. The pediment is usually scantily covered with vegetation allowing the streams to have maximum erosive and transporting effects. In the Mesozoic and earlier eras there were evidently few plants adapted to cover large areas of arid or semiarid terrain and therefore correspondingly more opportunity for pediment development.

Because of the limited extent of most modern pediments, they usually cut across rocks that differ little in structure or lithology from the adjacent high areas undergoing erosion. Theoretically there is no good reason why this should be universally true. If the rock fragments are durable enough and conditions of topography and climate are right the gravel

sheet might expand indefinitely and cover tremendous areas of diverse structure and lithology. Probably most recent pediments are relatively small; as known in North America they are located mainly in intermontane basins or in other areas where their limits are determined by mountain ranges and large rivers. In the past, when fewer mountain ranges and large rivers were present, correspondingly greater areas were available.

Most recent pediments in North America are at relatively high elevations in areas that have been undergoing degradation for long periods of time. They are temporary episodes in the long process of base leveling and will not become the dominant type of land form until the general surface approaches the level of the ocean. In the past, under suitable climatic conditions, pediments were probably initiated and expanded on land areas *after* long periods of aggradation and at elevations not greatly above base level. Thus the areas covered would be more extensive, and there would be almost perfect parallelism and agreement of structure between the pediment cover and the underlying rocks.

Most modern pediments will be destroyed and dissipated by erosion, but with the right combination of geographic situation and diastrophic movements such surfaces may be covered by subsequent deposits and preserved. No matter what sort of sediment may cover a pediment there is likely to be some reworking of loose surface material so that the contact will appear gradational. According to the usual terminology a buried pediment gravel would be called a basal conglomerate and would be assigned to the same general time interval as the overlying and probably thicker formation into which it apparently grades. Again the unconformity and most of the conglomerate are of essentially the same age regardless of the time involved, and the overlying beds may be much younger than their so-called basal facies.

Conclusions

If pedimentation has been active in the past in producing continental deposits and unconformities several implications are obvious. Such formations will be difficult to date owing to scarcity of fossils (which are rarely preserved in loose gravels near the surface), and because fossils of widely separated age may be brought into close association during the long time involved in producing, reworking, and transporting the gravel cover. It is illogical to assign the unconformity to one period and the gravel sheet to a much later period just as it is illogical to assume that the cutting of a pediment surface precedes in its entirety the production and dispersal of the gravel sheet which covers it. The lapse of time is represented by both the unconformity and the gravel sheet. In the case of the Shinarump it would seem best to assign it to a Middle Triassic age rather than to assume widespread uniform erosion for this interval.

If deposits such as the Shinarump are regarded as pediment accumulations it is possible to explain how great continental areas may be eroded with apparent uniformity but without even local sedimentation, or the production of residual deposits and soil profiles, and why very long time intervals are frequently involved in thin conglomerates.

The pediment cover is a special type of basal conglomerate if the latter term is used in a purely descriptive sense without genetic implication. The concept of pedimentation may be applied with profit to continental sediments just as the concep' of marine planation is useful in a study of marine stratigraphy. Since the processes and results of continental and marine sedimentation are vastly different it is probably an advantage to indicate clearly the differences by use of distinctive terminology. *Pedimentation and pedimentary deposit* may, therefore, be valuable terms for stratigraphers as well as for geomorphologists.

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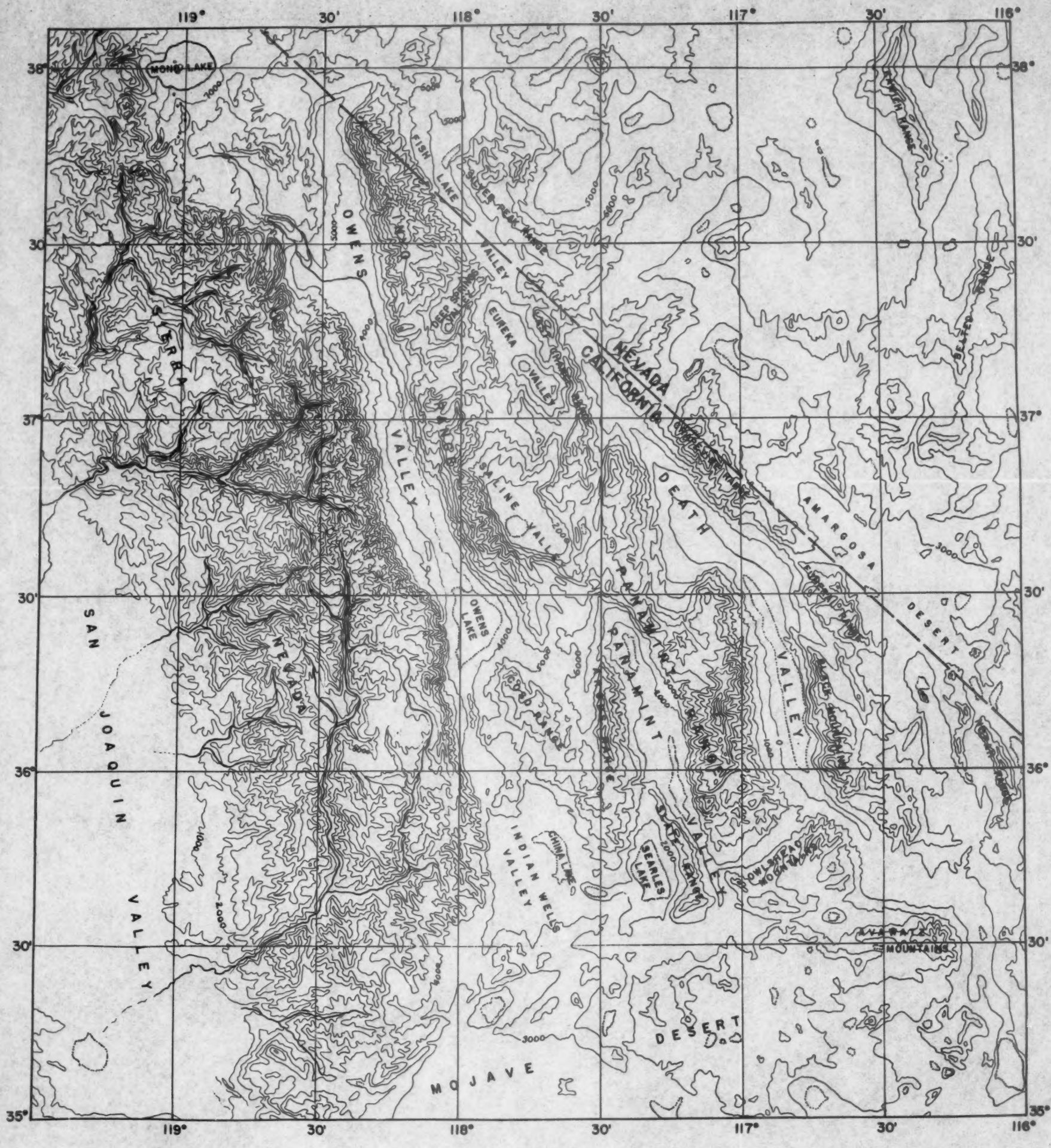

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CONTOUR INTERVAL 1000 FEET

BASIN AND RANGE PROVINCE OF SOUTHEASTERN CALIFORNIA

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PHYSIOGRAPHIC FEATURES OF THE PANAMINT RANGE, CALIFORNIA

By John H. Maxson

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Abstract

The Panamint Range, California, exemplifies many of the characteristic geomorphic features of basin ranges. The central part of the range was an inselberg on a pre-faulting surface of generally low to moderate relief developed in an arid climate. The Panamint block was brought into strong relief presumably by late Pliocene and early Pleistocene downfaulting of adjacent basin blocks on faults of variable dip. Movement was in part strike-slip; the Panamint Valley block moved northward and down with respect to the mountain block. In addition the Panamint block and adjacent depressed Death Valley block were rotated eastward. Fan remnants were uplifted on the Panamint Valley scarp, and alluvial fans were entrenched in Death Valley. Streams in the southern part of the west flank of the range cut valleys of V in V cross profile, and their longitudinal profiles developed convexities at and near the margin of the range because of successive uplifts or accelerations in uplift.

Introduction

Basin Range Theory and the Death Valley Region

The basin and range province of the western United States, from the Wasatch Range of

Utah on the east to the Sierra Nevada of California on the west, has long been an area of great geologic interest. Since Gilbert's original interpretation of the ranges as uplifted fault blocks (1874, p. 50; 1875, p. 21–42) many additions to and modifications of the structural theory have been made. Gilbert took little part in publicly modifying his original view during his lifetime, but his important posthumous summation *Studies of Basin Range structure* (1928) provided a wealth of geologic observation and interpretation.

Russell (1884) confirmed Gilbert's theory. Louderback (1904; 1923; 1926) established the relationship between structure and geomorphology and demonstrated its general applicability over a wide area of the Great Basin. Davis (1903; 1905; 1925; 1932b) systematized the sequence of geologic and physiographic events characteristic of basin ranges. A detailed account of the geologic history of the basin ranges may be found in Nolan's excellent summary (1943).

While some geologists were attacking Gilbert's fault-block theory and maintaining that the basin ranges are generally anticlinal in origin, Campbell (1904) described the Amargosa and Panamint mountains as tilted and eroded fault blocks. The Death Valley area between the ranges became a basin receiving sediments resulting from their erosion.

Death Valley and the Panamint Range were also described by Ball (1907, p. 195–212). He suggested that Death Valley is a block "dropped down between the bounding ranges by faults." General features of the faulting were later discussed by Noble (1926) and Davis (1927).

Acknowledgments and Objectives of the Study

The salient features of the geology of the Death Valley region were pointed out by Professor J. P. Buwalda of the California Institute of Technology on field trips beginning in 1927. The writer gratefully acknowledges this indebtedness. In 1930–1931 numerous visits to the Panamint Range with the late Professor John E. Wolff of Harvard University involved traverses of Redlands Canyon and Butte Valley.

In 1931, as a student of Professor W. M. Davis, the writer began a study of the features of the valleys of the Panamint Range. In 1932 Professor Davis suggested a joint paper treating physiographic features attributable to intermittent uplift deductively, and describing the scarps and valleys of the Panamint Range as observed. A field trip during 1933 blocked out the project. Professor Davis wrote an introductory statement tracing the development of the basin—range theory and outlining physiographic features expected as a result of intermittent uplift and rotation of a mountain block. Professor Davis' death, February 5, 1934, ended the work on the joint project. The writer deeply appreciates his obligation to Professor Davis both for general instruction during student days and for later discussing the phenomena in the Panamint Range.

The writer was away from California most of the time from 1936 till 1945 and was unable to return to the problem until 1946 when the stream profiles were plotted. He wishes to thank Professor J. Hoover Mackin for making valuable suggestions in the manuscript.

Location, Topography, and General Geologic Features

The generalized topographic map of the basin and range province (Pl. 1) shows the relationship of the Panamint Range to its neighbors. The great west-tilted fault block of the Sierra Nevada is bounded on the east by the long northwest trending Owens Valley. The Inyo Range is the highest and longest of the individual ranges, and the Panamint Range is next in height and size.

The Panamint Range is about 80 miles in length and averages 14 miles in width. The main part of the range, the part principally considered in this paper, has a single, simple north-south trending crest line (Pl. 2). Telescope Peak is 11,045 feet above sea level; to the west South Panamint playa is 1046 feet above sea level; to the east Death Valley playa in one area fringing the Black Mountains base reaches 279.6 feet below sea level. The map underemphasizes the abrupt, rectilinear outlines of the scarps forming the west fronts of the Panamint Range and the Black Mountains, and distorts somewhat the deep, narrow canyons trenching the range faces.

The great mass of the range consists of pre-

FIGURE 1. WEST SIDE OF PANAMINT VALLEY
Looking northwest from altitude of 8000 feet above Panamint Valley.

FIGURE 2. EXTENSION OF DARWIN ARID SENESLAND AROUND NORTH END OF PANAMINT VALLEY OVER COTTONWOOD MOUNTAINS
Looking southeast from altitude of 9000 feet above south end of Saline Valley.

ELEVATED LOW-RELIEF SURFACES AROUND PANAMINT VALLEY

FIGURE 1. WILDROSE SEGMENT OF WEST FRONT OF PANAMINT RANGE
Arrow points to beheaded stream channel of Wildrose Creek on old fan. Dotted line follows mountain-facing fan scarp of Wildrose graben. Dashed line indicates trace of an outer fan fault. Looking east from altitude of 8000 feet above Panamint Valley.

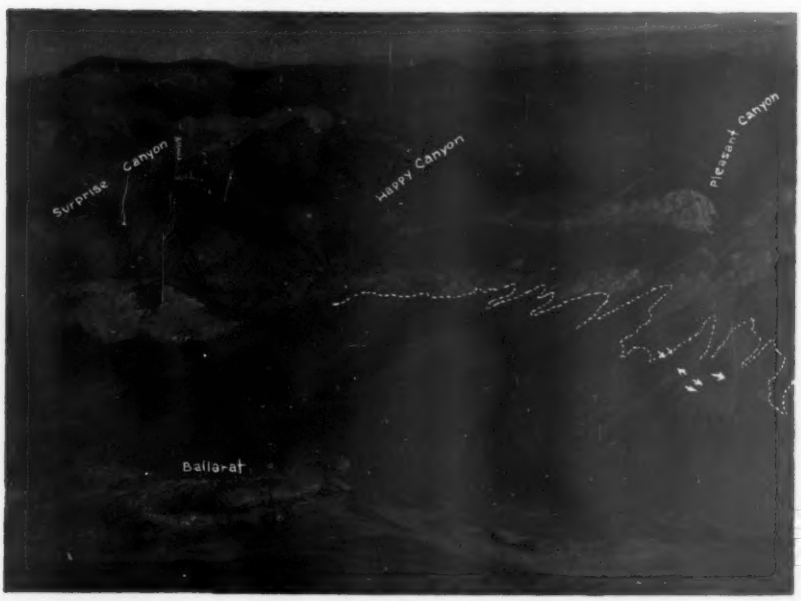


FIGURE 2. WEST FRONT OF PANAMINT RANGE AT PLEASANT CANYON REENTRANT
Ballarat fan in right foreground. Arrows point to supposed shore lines of Pleistocene Lake Panamint. Contact of older alluvium on bedrock of scarp shown by dashed line. Looking east from altitude of 8000 feet above Panamint Valley.

Mesozoic sedimentary rocks and late Jurassic granite. At the base is the Panamint metamorphic complex (Murphy, 1932) of quartz-mica paraschists, actinolite schists, marble, and conglomeratic schists. They outcrop on the west flank of the range and are overlain unconformably by Murphy's Telescope Group, which includes moderately metamorphosed dolomites and quartzites. This group forms the crest of the range. Noble (1934, p. 174) suggests that the Panamint metamorphic complex is Archean and that the Telescope Group is Algonkian. Dipping homoclinally east on the east flank of the range, 30,000 feet of Paleozoic strata is recorded by Hopper (1947, p. 404).

The structure of the Panamint Range is broadly anticlinal, plunging to the south; the axis is west of the crest line. Deformation during the late Jurassic Nevadan orogeny was accompanied or followed by batholithic intrusions of granite. Numerous faults occur within the range, but most of them antedate the period of basin-range faulting and do not have topographic expression resulting from displacement.

General Features of the Powell Surface (Darwin Arid Senesland)

The pre-uplift surface—the Powell surface—(Davis, 1925, p. 388) was one of variable relief in this region. The summit area between Argus and Inyo ranges is a remnant of the Powell surface having relief of 2500 feet (Pl. 3, fig. 1). Broad basins with residual ridges and peaks are present. It is a surface of late maturity to early old age in the arid cycle of erosion. This differs from the late mature to early old-age surface of the humid cycle in that locally high relief and prominent scarps may still be present, and stage in the cycle is related to the ratio of area of residual mountain mass to the area consumed by mountain-front retreat or pediplanation. Distinction between surface forms and sequence in the various stages of the erosion cycle in humid and arid climates has previously been outlined (Maxson and Anderson, 1935). Here and there inselberge of considerable size interrupted the broad sweeps of low country. These inselberge or inselberg ranges occupied the positions of the present highest areas. Thus an ancestral Argus Range, whose Maturango Peak is now 8850 feet high, rose some 4000 feet above the broad low-lying surface to the north.

The Panamint Range itself was an inselberg range on the pre-uplift surface. Relatively few low-relief remnants are found, and these were marginal to the mountain mass as it existed before upfaulting. These remnants have altitudes from 4500 to 6500 feet which, in the absence of fault displacement of the period of basin-range uplift, indicates a relief of 2000 feet. Telescope Peak, whose present altitude is 11,045 feet, rose some 6000 feet above the general level of the landscape.

The ancestral mountain ranges of the Powell surface in southeastern California are elongate in a north-south direction, which in general parallels the regional strike of their component sedimentary rocks. They were residual masses in the erosion of which internal structure played an important role.

In the easternmost basin range, the Wasatch Mountains, Eardley pointed out (1933) that relief was at least 3000 feet before basin and range faulting began. He noted a pronounced topographic unconformity where the fault-scarp topography of the Wasatch front breaks suddenly into a submature surface. The range-surmounting surface differs from that of the Panamint-Argus-Inyo region of southeastern California in possessing a finer dissection pattern not inconsistent with erosion under humid climatic conditions and in being in a more youthful stage of the normal cycle of erosion. The California surface, in reduction of area of mountainous residuals, had progressed considerably beyond maturity in the arid cycle yet does not show the near obliteration of inselberge expected in advanced old age. It might well be termed a "senesland," a land surface intermediate between matureland and peneplain, as defined by Davis (1932a, p. 429), which the writer now prefers to the term "oldland" (Maxson and Anderson, 1935, p. 90, 94). The surface would further be described as an arid senesland. The largest remnant of this surface is the plateau between the Coso and Argus ranges on the south and the Inyo Range on the north. The Darwin mining district is located on this plateau, and near by is Darwin Wash, which was in pre-uplift time an enclosed basin. The Powell surface of this part of the Great

Basin is therefore named the Darwin arid senesland.

Low-relief Remnants of the Darwin Arid Senesland in the Panamint Range

Cottonwood Mountains

The Panamint Range north of Emigrant Wash, sometimes called the Cottonwood Mountains, has numerous summit flats having an altitude from 6000 to 7000 feet. These flats are accordant and continuous with the plateau summit south of the Inyo Range (Pl. 3).

Tucki Mountain

An extensive surface of low relief, on which Tucki Mountain (elevation 6705 feet) stands as a prominence, forms the summit of the Panamint Range south and east of Emigrant Wash. The Tucki surface proper averages 5500 feet in elevation. The topographic unconformity between the Tucki surface remnant and canyons of the Death Valley side is the most striking one in the Panamint Range.

Harrisburg Flat-Wildrose Canyon

South of Tucki Mountain and north of the Telescope Peak ridge are two large nearly enclosed smooth-floored basins which are contiguous but separate in drainage. Harrisburg Flat (Pl. 2) is about 700 feet lower than the Tucki surface. The headwaters area of Wildrose Canyon is roughly accordant with Harrisburg Flat. These basinlike features, cut at a lower level than the Tucki surface, doubtless postdate it and developed after a small initial uplift. However, in the sense that they antedate the major upfaulting responsible for the Panamint Range as a whole they are part of the Darwin arid senesland. The coexistence of surfaces cut at somewhat different levels in an arid region is now generally recognized, and no great interval between times of formation is inferred. These near-basins like true basins in an arid region are expanding laterally by retreat of the enclosing mountain slopes since they provide local base levels controlling the erosion of flanking pediments.

Middle and South Parks

The Wildrose low-relief surface flanks the northern end of the central Panamint Range crest or Telescope Peak ridge. Toward the south the relief becomes stronger on the west side of the ridge. However, a zone of broad valley development is found in major stream valleys from 5500 to 6000 feet in elevation. The wide upper valleys begin on the north with tributaries to Wildrose Canyon and end on the south with Middle and South parks. Parklike stretches occur in the upper part of Surprise Canyon and in the upper part of Pleasant Canyon. The broad valley and park development, because it can be traced southward from the Wildrose broad valley, is considered contemporaneous in development with the low-relief plateau summit surrounding the north end of Panamint Valley. It therefore should be considered a part of the Darwin arid senesland.

Middle and South parks are very elongate, east-west basins on the west slope of the south end of Telescope Peak ridge. They are parallel, and each has a playa floor at about 6000 feet elevation. Each has an area of several square miles (Pl. 5, fig. 1; Pl. 7, fig. 2). The basins open to the west above the freshest and highest section of the Panamint fault scarp. Between the playas and the canyons cutting the scarp are typical V-shaped valleys about 2 miles in length. The cross profile of the outlet valleys from South Park and Middle Park is shown in Figure 2 of Plate 7. Near the west end of South Park is a low divide 6030 feet in elevation as measured by Paulin altimeter. South Park playa is 5955 feet in elevation. No fault-block displacement could be found to account for this 75-foot obstruction to westward flow of water from the headwaters of South Park to South Park Canyon in the scarp. It does not seem plausible to postulate a sharp upwarping fortuitously localized in the valley above the scarp which would thus dam the headwaters area. Nor does it seem likely that the parks were originally two long, parallel, enclosed basins each of which has fortuitously almost been tapped by consequent streams of the fault scarp. They are elongate across the strike of the underlying rocks, and the parks, fault-scarp canyons, and connecting V-shaped val-

leys are in perfect alignment. A more reasonable explanation would involve considering the parks analogous in origin to the broad valley stretches of Pleasant Canyon and Surprise Canyon to the north. The low-gradient headwaters could have been impounded by relatively rapid rotation of the range. Perhaps aiding in impoundment and the formation of wind gaps was weakening of the streams by loss of watershed area in downfaulting of Butte Valley to the east. (*See* Plate 2 for relationships.) The present elliptical form of the parks would be explained as the result of recession of valley sides and pediment formation with respect to the local base levels.

Butte Valley

Butte Valley is a roughly crescentic shaped depression below and south of the Telescope Peak ridge. Its elevation ranges from 4000 to 5000 feet and is about 500 feet lower than the low-relief areas in the headwaters of Six Springs Canyon and Hungry Bills Ranch to the north on the east flank of the crest. Butte Valley is believed to be a graben since it is oblique to the axis of the range. It cuts across regional strike of the strata and possesses an anomalous relationship to the stream valleys draining it. Like other high-lying near-basins it has been subject to valley-side recession and is still being modified independently of other range interior surfaces. Figure 1 of Plate 6 shows how Butte Valley communicates west through a V-shaped valley with Redlands Canyon draining to Panamint Valley. This is also shown by Plate 2. The V-shaped notch suggests that Butte Valley once drained westerly to Panamint Valley. The north part now drains down Warm Springs Canyon, and the south part down Anvil Springs Canyon to Death Valley. East-sloping louderbacks south of Warm Springs Canyon and gentle-surfaced ridge crests to the north point to the existence of the Darwin arid senesland southeast of the Telescope Peak ridge.

Age of the Darwin Arid Senesland

Probable limits in time of erosion of the surface are afforded by paleontological evidence from sedimentary rocks believed to antedate the major basin-range uplift because of folding, tilting, and faulting; and by fossils from formations deposited in basins made by the fault-block uplift. Thus Hopper (1947, p. 400–401) correlates the Ricardo erosion surface, a pediplain cut on tilted lower Pliocene (Merriam, 1919, p. 529) Ricardo beds and on granite, with the Darwin surface because both surfaces bear flows of olivine basalt. He considers that the Coso beds, late Pliocene or early Pleistocene according to Schultz (1937, p. 86–98), were deposited on the flank of the uplifted Coso Range. Cutting of the surface is limited to the interval between lower Pliocene and Pleistocene.

From the Avawatz Mountains, southeast of the Panamint Range (Pl. 1), Henshaw (1939) has described a lower Pliocene vertebrate fauna from folded and faulted fluviatile and lacustrine arkoses and tuffs. The deformation took place presumably during uplift of the range. A fairly even erosion surface was developed over the folded strata, and on this surface a conglomerate of presumed Pleistocene age was deposited. The Avawatz sequence strongly suggests that the period of extensive erosion occurred in Pliocene time.

Panamint Range Faults and their Physiographic Expression

Fault Pattern

Having examined the relief and distribution of remnants of the erosion surface developed prior to basin-range faulting, the areal pattern and character of the faults on which displacement leading to present relief was accomplished will be outlined. On the west side of the Panamint Range great rectilinear scarps with aligned truncated interfluve spurs testify to magnitude and relative recency of movement. On the east side of the range direct evidences of recent faulting are scarce, yet great earlier displacement may be inferred.

Noble (1926) wrote:

"The Death Valley and Panamint Valley faults . . . are exceedingly irregular in detail. Neither is a straight continuous fault; they are, rather, a succession of faults, each of which is offset from the other along the strike. Consequently their escarpments have a roughly zig-zag pattern and are indented by

great concave bights or cusps where the offsets occur. At some places the bights mark cross-faults; at others they appear to represent areas of great and sudden downwarp. At many places the faults exhibit enormous changes in amount of throw in distances of a few miles. Actually the rock masses in the escarpments along the Death Valley and Panamint Valley faults are a series of tilted crustal blocks which have been displaced very irregularly and unevenly."

The writer has seen no single fault plane which could be demonstrated as the one on which principal range uplift occurred. A principal fault plane or fault zone must be inferred near the base of the great scarp buried under fans which overlapped the bedrock scarp concurrently with displacement. Fault planes of auxiliary faults are seen within the mountain mass beneath the scarp. Physiographic evidence of auxiliary faults basinward from the scarp is afforded by fan scarps and scarplets. Information regarding fault attitudes, positions, and direction of relative movement must be obtained from observations of the auxiliary faults.

Fan Scarps of Panamint Valley

Gilbert (1928, p. 37) interpreted scarps in alluvium parallel to the mountain front as evidence of a frontal fault. He gave a detailed description (1928, p. 33–39) of various types of scarps and interpreted hollows bounded by scarps as grabens or as chasms filled with slumped debris. Page in his study of the 1915 fault scarp in Pleasant Valley, Nevada (1935, p. 698–700), noted small nearly vertical scarps in alluvium produced by rending apart alluvium clinging to fault surfaces. The fault planes have lower dip where exposed, and the fan scarp thus reveals the approximate trace but not the true dip. Sharp (1939, p. 906–907) modified Gilbert's concept by illustrating the overlap of alluvium onto the mountain block covering the fault trace. The hollow was derived by slumping and deposition of gravel in the open trench, following Gilbert's idea.

Three types of displaced fanglomerate indicate faulting on the west front of the Panamint Range. (1) Patches of fanglomerate are isolated above the base of the major or bedrock fault scarp. Davis often verbally referred to such patches as fan welts or welts because the gravel adhered to the mountain front like a welt. In a somewhat unusual example the welt rests against a fault plane (Pl. 7, fig. 1). The welt indicates uplift of the scarp with respect to the present level of alluvial-fan deposition. (2) Fan remnants along the base of the scarp are "hanging" above the present surface of fan deposition, separated from it by a basinward-facing fan scarp. (3) A special kind of fan scarp lies some distance from the mountain front out on the fan surface and faces either mountainward or basinward. Since the fault trace is usually nearly parallel to the mountain front while the fan axes are nearly perpendicular to it the scarp top and base may be imagined as described by nearly concentric arcs. The displacement shown is generally small.

At the mouth of Wildrose Canyon an enormous alluvial fan (Pl. 4, fig. 1) is separated from hanging fan remnants of the range front by a broad trench which has often been referred to as "the Wildrose fan graben." The trench north of Wildrose Canyon averages 2 miles in width but narrows to the south to less than a mile in width. Scarps 200 feet high face the trench in its central part and diminish in height to the north and to the south. In the northern part of the fan drainage lines were maintained during the movements bringing the trench into being. Opposite the present mouth of Wildrose Canyon on the basinward fan segment a major valley 100 feet deep was cut by Wildrose Creek during a period of fan dissection preceding formation of the trench. The beheaded valleys of the old dissected Wildrose fan now have underfit streams which run only during heavy rains. Since no fault planes are visible, evidence for graben depression is solely physiographic. The basinward scarp terminates in the south part of Wildrose fan. There the hanging fan of Tuber Canyon is separated from the downdropped fan surface by a single basinward-facing fan scarp. The Wildrose trough has been extensively alluviated by Wildrose Creek and Tuber Creek since its formation.

A break in the fan surface marking a boundary between older and younger surfaces of deposition may be noticed from the air where no break in slope or color is discernible on the

FIGURE 1. SOUTH PARK CANYON SEGMENT OF PANAMINT FAULT SCARP
Contact of older alluvium on bedrock of scarp shown by dashed line. Base of fan scarplets shown by solid lines. Looking east from elevation of 8000 feet above Panamint Valley.

FIGURE 2. OBLIQUE VIEW DOWNWARD ON PANAMINT FAULT SCARP NEAR SOUTH PARK CANYON
Looking down from altitude of 6000 feet just above plane of projection of interfluve crests.

PANAMINT FAULT SCARP SOUTH OF BALLARAT

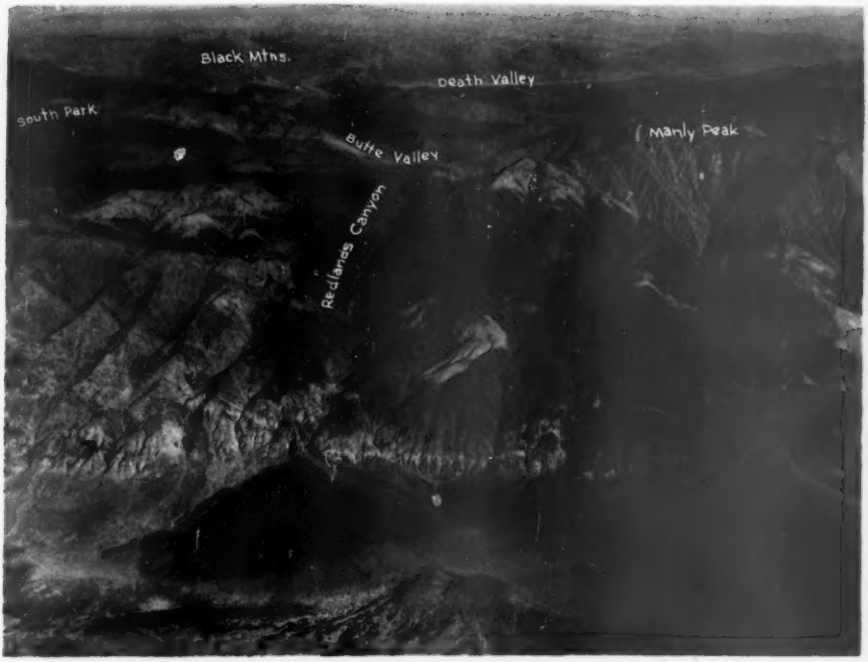


FIGURE 1. REDLANDS CANYON SEGMENT OF PANAMINT FAULT SCARP
Looking east from altitude of 8000 feet above Panamint Valley.

FIGURE 2. HANAUPAH CANYON SEGMENT OF EAST FRONT OF PANAMINT RANGE
Note dissected and reconstructed elements of Hanaupah fan and Hanaupah fan scarplet.
Photograph by U. S. Army Air Corps.

REDLANDS CANYON SEGMENT OF WEST PANAMINT FRONT AND HANAUPAH CANYON SEGMENT OF EAST PANAMINT FRONT

ground. It is interpreted as reflecting displacement of the fan surface above a fault in the basin bedrock, the older alluvium being more weathered and darker than the younger alluvium of the reconstructed fan surface.

South of Wildrose and Tuber canyons and north of Happy Canyon fan scarps are missing. At the mouth of Pleasant Canyon is the hanging fan of Ballarat (Pl. 4, fig. 2). Fan scarps 100 to 200 feet in height extend south from the northwestern extremity of the Ballarat fan almost to Redlands Canyon. Fan scarplets occur on the South Park Canyon fan (Pl. 5, fig. 1), the Redlands Canyon fan (Pl. 6, fig. 1), and the Manly Canyon fan (Pl. 6, fig. 1). The fan scarplets on these fans face the range and indicate a small upward movement of the basin with respect to the range. In the photographs the fan distributaries may be seen to be deflected laterally by the scarplets. A similar relationship may be seen on the west side of Panamint Valley (Pl. 3, fig. 1).

Fault Scarp of West Front of Panamint Range

The Panamint scarp south of Wildrose Canyon is breached by Tuber, Jail, Hall, Surprise, and Happy canyons. This section of the scarp is rectilinear, and the great interfluve facets are trenched by numerous gullies and minor canyons. The scarp slopes basinward about 25°, and its base is lapped by encroaching fans. At Pleasant Canyon (Pl. 4, fig. 2; Pl. 5, fig. 1) the scarp curves out abruptly for about 2 miles, then again resumes a north-south direction with the fresh-appearing face rising higher and higher, reaching a maximum of 5000 feet above Panamint playa in the vicinity of Middle and South Park canyons. Old alluvial fans, the largest of which is the Ballarat fan at the mouth of Pleasant Canyon, lap far up on the scarp. The contact is depositional and for the most part low angle.

Observed Fault Planes in the Mountain Block

Near the mouth of Redlands Canyon both high- and low-angle normal faults are found. On the south side of the canyon at an elevation of 1650 feet (Pl. 7, fig. 1) a large expanse of slickensided fault plane is exposed. It strikes N. 10°W. and dips 30° basinward. This low-angle fault plane outcrops on the eroded scarp back of faults dipping 60°–70° basinward. A fall at the mouth of Redlands Canyon has retreated headward in brecciated quartzites whose principal planes dip 68°W. The steep-angle marginal faults displace the low-angle fault plane mentioned above and are therefore younger. Hopper (1947, p. 426) records a 65°W. dip for one of the step faults north of Wildrose Canyon. This is a marginal fault.

Relationship of Fault Scarps to Fault Planes

There has been much speculation regarding the possibility that the fresh-appearing fault scarps of the west front of the Panamint Mountains between Ballarat and Redlands Canyon and of the Black Mountains south of Mormon Point in Death Valley are actually at or near the fault planes. Some geologists maintain that the scarps are so little dissected that they must approximate the fault planes. Others consider that erosion could never be so slight during the time required for relative earth movements of several thousands of feet. Most of the literature emphasizes erosional modification of fault scarps.

Gilluly (1928, p. 1113) cited a number of instances of spurs with triangular facets and associated fault planes. The fault planes he observed at the front of the Oquirrh Range dipped 40°–80° with an average of 50°. The triangular facets sloped at angles of 21° to 30°. A similar discrepancy between the fault scarp and fault plane of Plum Ridge east of upper Klamath Lake, Oregon, was studied by Gilbert (1928, p. 76–80). The average dip of the fault plane, 49°, is considerably steeper than that of the scarp which is about 34°. The degradation of this scarp, according to Gilbert, has been accomplished largely by disintegration and transportation of rock fragments by gravity because the slope of the scarp corresponds to the angle of repose. The slope of the spur north of Redlands Canyon is more or less uniform at 25°–30° over both bedrock and fanglomerate. Since the frontal faults dip 60°–70° W. this spur shows considerable reduction in slope attributable to erosion.

The writer hoped he might be able to detect

stages in the intermittent uplift of the Panamint Range in successive reductions in slope of the fault scarp from lowest to higher portions of the range. However, no marked or abrupt changes in slope were found. In general, slopes of 5°–15°W. characterize the area west of the summit, 20° in a large well-dissected area in the upper part of the scarp, and 30° in the lower part of the scarp. The fan scarps range from 30° to 80° in west slope.

At the Pleasant Canyon re-entrant the fault scarp was exposed to erosion during the period of time required for growth of the Ballarat fan to an elevation of over 1000 feet above the present basin floor. The fans antedate earliest Wisconsin, hence the scarp has been subject to erosion throughout late Pleistocene and Recent time. Yet it shows remarkable regularity and passes southward into steeper parts of the scarp with no marked break.

Near Redlands Canyon a well-defined fault plane in the scarp dips 30°W., approximately the slope of the scarp itself in this vicinity. This plane was protected from erosion by an overlying mass of bedrock (Pl. 7, fig. 1). The fact that the plane cuts massive gneiss and granite precludes its being a landslip plane of local significance only. The fanglomerate of the hanging wall is brought into contact with the bedrock of the footwall demonstrating a minimum displacement of some tens of feet, but the displacement may be many hundreds of feet. Though one may not conclude from this one example that the fault scarp possesses exactly the attitude of the fault on which it was elevated, it nevertheless suggests that the scarp is eroded in an important fault zone.

The geomorphic evidence is perhaps even more speculative than the geologic evidence. Observers have attempted to determine just how closely the interfluves of the scarp approximate a plane or regularly curved surface. Distance from the eye and distortion of perspective have interfered with such visual determination and led to contradictory opinions. The writer believed the field evidence might be presented photographically by selecting a point in the air just above the projection of a hypothetical plane described by the interfluves of the fresher lower portion of the scarp. The photograph would then be taken looking obliquely down the plane. Though aerial acrobatics in proximity to the scarp were necessary, some degree of success was attained in obtaining the desired view. Figure 2 of Plate 5 is such a view looking down the scarp shown from the front in the lower right part of Figure 1 of Plate 5 just to the south of South Park Canyon. The interfluves show remarkable alignment. The rocks in this part of the scarp are in place in the interfluve crests, not in weathered fragments or loose joint blocks at the angle of repose. The form of the scarp strongly suggests that in general it has not been much eroded beneath the fault zone on which it was elevated.

H. D. Curry (oral communication) has indicated his belief that the Panamint scarp is a "turtleback," the stripped sole of a warped thrust fault (Curry, 1938). It has a low angle of inclination, though not so low as commonly found on turtlebacks of the Black Mountains, and it shows some evidence of stripping in a fault zone. But unlike the Black Mountains features no remnants of young, over-riding rocks are found on the Panamint scarp. Moreover, it is difficult to visualize the scarp as having been formed by stripping of erosion-resistant, Precambrian quartzites and gneisses of a hanging wall everywhere just down to the Precambrian metamorphic rocks of the footwall. The basinward block appears to be downdropped on a low-angle, oblique-slip, normal fault. The horizontal component of slip indicates the operation of a horizontal couple or shearing stress. Since the striations are rectilinear and oblique it would appear that displacement resulted from a combination of tensional and shearing stresses. Like the Black Mountains turtlebacks the Panamint scarp has a huge undulation (at Pleasant Canyon re-entrant), but it could not have been caused by warping because the stratified formations in the mountain block do not show similar deformation. It was not caused by cross faulting because separate cross-faults were not found. Presumably, the huge crenulation was formed directly by fracture resulting from the initial stresses. Steep-angle normal or gravity faults, more typical of current concepts of basin-range faults, are limited to the margins of the mountain block and show the most recent activity.

FIGURE 1. FAULT PLANE ON SOUTH SIDE OF REDLANDS CANYON
Fanglomerate rests on bedrock of hanging wall block.

FIGURE 2. WIND GAPS OF SOUTH PARK (left) AND MIDDLE PARK (right)
View looking west over high-lying basins on west flank of southern Panamint Range.

INTERNAL FEATURES OF THE PANAMINT RANGE

Direction of Movement on Faults

The low-angle fault south of Redlands Canyon has striations striking N. 48°W. although the strike of the plane is N. 10°W. The striations indicate a large strike-slip component, the range having moved up and to the south with respect to the basin. In 1934 the writer observed a strike-slip component when offset streams were photographed on the range margin just south of the Panamint Valley-Emigrant Pass road (Hopper, 1947, Pl. 3, fig. 2). The recent strike-slip movement shown by the stream offsets was relatively south for the range and north for the basin.

Nature of Fault Displacement

The Panamint Range block certainly moved up with respect to the Panamint Valley block, but absolute movement during basin-range orogeny in this part of southeastern California may have been just elevation of ranges or just settling of basins or a combination of the two movements. Dislocations of the Darwin arid senesland within the ranges show that the various blocks underwent some differential movement. Also, as shown here, the Panamint Range has been rotated eastward. However, two lines of reasoning suggest that the major relief was developed by downfaulting of the basins, not upfaulting of the ranges.

The Darwin arid senesland shows a general accordance in elevation from range to range. Where the Panamint Range joins the Argus Range (Pl. 1; Pl. 3, figs. 1, 2) the pre-faulting erosion surface passes from range to range without apparent disturbance. The basins, however, vary in elevations. South Death Valley playa is at an elevation of 279.6 feet below sea level, while south Panamint playa lies at 1046 feet, Saline Valley playa 1100 feet, Owens Valley at Owens Lake 3600 feet. Although the amount of basin filling is unknown in each separate basin the great differences in elevation of the existing playas virtually require initial differences of considerable magnitude in the elevation of the bedrock floors. The logical assumption would then be that basin floors were downdropped varying distances below the original base level.

Some evidence suggests that the most recent scarps in alluvium were formed after the disappearance of a late Pleistocene Panamint Lake. Campbell (1902, p. 20) observed wave-cut terraces on the high-lying fan surfaces near Ballarat. Gale (1915, p. 312–317) took barometer readings on these and other shore lines and found that they agreed in elevation closely with the 1977 feet elevation of Wingate Pass, lowest point on the periphery of Panamint Basin. Particularly he noted two "distinct shore benches" at 1950 feet and 1970–1980 feet on the west side of Panamint Valley southwest of Ballarat. Northwest of this locality at Shepherd Canyon lava flows cap extensive deposits of onyx marble and calcareous tufa at this elevation. These deposits were formed by springs near the lake margin. The flows and spring deposits are cut by faults of small displacement on which the basinward side has been depressed. The faulting thus post dates the lake. The truncated fanglomerate cliffs of the Ballarat fan (Pl. 4, fig. 2) stand 200 feet above the adjacent playa. The steep fan scarps near South Park Canyon (Pl. 5, fig. 1) are up to 100 feet in height. The relatively unconsolidated gravels could scarcely have maintained the marginal precipices for a considerable period under the water of the lake and throughout the post-lake erosion. It is therefore believed that latest fault displacements in Panamint Valley postdate the existence of the lake.

Blackwelder (1933, p. 470) believes Panamint Lake was formed by overflow of the Owens River through Searles Lake basin probably in the Tahoe glacial age (earliest Wisconsin). The shore lines were probably originally faint features, having been cut in a brief period of time, but they have been almost destroyed by post-lake erosion. The shore lines, as Gale emphasized, wherever found, appear undisplaced. The writer obtained Paulin altimeter readings on terrace benches on the highlying South Park Canyon fan at 1830 feet and 1980 feet. The higher bench was developed both north and south of the canyon. If the high-level mark of the lake is everywhere nearly in accord with the point of overflow into Wingate Pass (1977 feet) the range blocks have not been displaced much with respect to each other by post-lake faulting. The post-lake faulting would

involve merely downdropping of the basin floor.

Fan Scarps on West Side of Death Valley

Many geologists have followed Campbell (1902, p. 19) in regarding Death Valley as the downtilted and partially buried backslope of the Panamint Mountains block. The lack of alignment of spur terminations and the fan-embayed valleys certainly indicate that there is no continuous frontal fault as on the western margin of the range. However, several miles east of the east front discontinuous fan scarplets are found on several fans. Near the south end of Death Valley, Anvil Springs Canyon fan shows vague fan scarplets. The Warm Springs fan to the north has several distinct fan scarps. The north part of the lower Hanaupah fan has a fresh-looking low scarplet (Pl. 6, fig. 2) about 30 feet high which extends north-south for over 2 miles. Scarplets also occur in the alluvium north of Poison Spring northwest of Furnace Creek Ranch.

The fan scarplets east of the Panamint Range in Death Valley indicate active faulting. This movement may be a recurrence of displacement on faults which earlier blocked out the east side of the range. If so, the scarp has retreated far westward and has been deeply dissected. In any case the part of Death Valley, lying east of the scarplets, is an orographic block structurally distinct from the Panamint Range block.

Valley Forms of the Panamint Range

Cross Profile of Valleys on the West Flank

The larger canyons of the Panamint scarp south of Ballarat resemble each other closely in development of V in V side walls. The lower parts of the walls are 80° to vertical, the intermediate walls average 40° to 50°, while the upper side slopes range from 25 to 30°. This V in V cross profile is not related to geologic structure or differences in rock types.

Redlands Canyon is typical in showing three major breaks in sidewall slope. The multiple V development is most prominent in the lower middle part of the stream course. Here the canyon is cut deepest into the range. The headwaters area near the junction of Redlands Canyon with Butte Valley at 4600 feet is broad, and the slopes of valley walls are close to the angle of repose of the rock fragments. Downstream the valley walls come closer together, and the cross profile becomes a steep V. About 3½ miles above the fall the stream enters a gradually deepening gorge. At 1½ miles above the fall the gorge reaches its maximum depth of 250 feet. Here side slopes above the gorge of 52°, 38°, and 23° may be measured. The gorge shallows as the range front is approached until just above the fall it is only 20 feet deep.

The V in V cross profile is interpreted as the result of breaks in rate of downcutting of the stream. The successively steeper walls are taken to indicate intermittent acceleration of rate of uplift with respect to base level (basin level). In all canyons traversed the steep gorges are associated with steep gradients of 10°–13°.

Longitudinal Stream Profiles as Indicators of Fault-Block Displacement

Longitudinal profiles of streams are normally concave upward, and the gradient, steepest in the headwaters, diminishes in downstream direction more and more gradually as base level is approached. Under stable crustal conditions the gradient is reduced throughout its length with passage of time; the reduction normally is progressively greater toward the source. However, gradient is but one of a number of interrelated factors defining the character of a stream. Gradient, discharge, and channel form control velocity which in turn determines maximum size of fragments which can be transported. Irregularities in velocity within the body of flowing water, turbulence, augmented by channel irregularities may increase the size maximum above that permitted by the mean forward velocity. Discharge and velocity determine the total load capacity. In turn the total load and maximum fragment size exercise a reciprocal control on velocity and gradient.

A stream flowing in a valley cut in a mountain mass of consolidated rock, during early stages of the erosion cycle from youth to maturity, usually does not have sufficient load to tax its carrying power. It is typically an un-

graded stream eroding its course throughout its length. Mackin emphasizes the contrast in character of graded and ungraded streams (1948, footnote p. 483):

"Slopes of ungraded stream segments are determined by the depth to which the stream has cut downward. In headwater basins in bedrock fairly uniform in resistance to corrasion the ungraded profile tends to decrease in declivity in a downvalley direction, the reason being downvalley increase in discharge and therefore corrasive power. Ungraded profiles of this type are superficially similar to graded profiles but they are completely different in origin; the ungraded profile is conditioned by the corrasive power of the stream, bedrock resistance to corrasion, and the length of time that the stream has been downcutting, while the graded profile is an adjusted slope of transportation that is influenced negligibly, if at all, by these factors."

Among the factors influencing gradient, the erodability of the bedrock of the channel is important. Factors determining the relative ease of erosion of different types of channel rock include ease of dislodgement of discrete fragments or particles (favored by jointing, weathering, weak cementation, lack of metamorphism, coarser crystalline textures with soft interstitial minerals, etc.), size of fragments or particles dislodged, type and number of tools available, and solubility. The gradient of the ungraded stream is lower immediately upstream from more erosion-resistant rock masses of the channel and higher at the downstream margin of these masses.

Obviously, where the upstream segment of a stream is uplifted with respect to the downstream segment gradient is increased. This steepening differs from the steepening caused by an erosion-resistant rock mass in the channel in that in time it is gradually obliterated by extension of an increased gradient upstream. This process distributes a steeper gradient over a longer and longer course. In the ungraded stream a steep gradient is maintained in fixed position at the downstream margin of the resistant rock mass. In analyzing the longitudinal profiles of Panamint streams which are youthful and ungraded steep gradients caused by displacement with lowering of base level must be distinguished from those caused by local differences in channel erodability. In a discussion of graded streams which seems also applicable to ungraded streams, Mackin (1948, p. 498) states:

"Lowering in base level, is in so far as the response of the stream is concerned, essentially the same as the lowering of a barrier in its path. Each small lowering of the control point steepens the gradient immediately upstream. Accelerated velocity in the steepened portion results in downcutting, and the steepening is propagated up-valley. Downcutting must continue until the slope is again completely adjusted to supply just the velocity required to transport all of the debris shed into the stream; as in the last case, and with the same qualifications, the final readjusted profile will tend to parallel the original profile."

The streams on the west front of the Panamint Range should have abnormal longitudinal profiles resulting from upfaulting of the mountain block. The degree of difference from normal profiles may afford a new measure of rate of uplift.

Method of Reconnaissance Survey of Longitudinal Profiles

Traverses of several major canyons were made in a jeep taking speedometer readings every tenth of a mile for horizontal control and Paulin altimeter readings for vertical control. Several sources of error can be considerably reduced. Most speedometers have individual idiosyncrasies, and the mileage recorded varies considerably with stage of wear and inflation of tires. Comparison with a measured mile showed the one used to have a positive error of 5.8 per cent. The most significant error in measuring was incurred when the road deviated from stream wash to terrace and back; an estimate of stream-wash distance was then used. The error in Paulin altimeter readings caused by barometric changes was kept at a minimum by checking the elevation at a bench mark prior to and after each traverse. The amount of vertical error which can accumulate during such a traverse does not materially alter the form of the profile.

The profiles (Pls. 8, 9) were originally plotted on a horizontal scale of 500 feet to the inch and were reduced photographically. The stream

courses on the upper portions of fans were plotted for comparison with the valley profiles. The position of the mountain front and bedrock-alluvium contact is indicated, but the vertical line at the contact is conventionalized and does not represent a vertical fault. The horizontal lines in portions of some of the profiles, used to carry elevations, are terminated to the right by a straight line and thus show places and amounts of convexity.

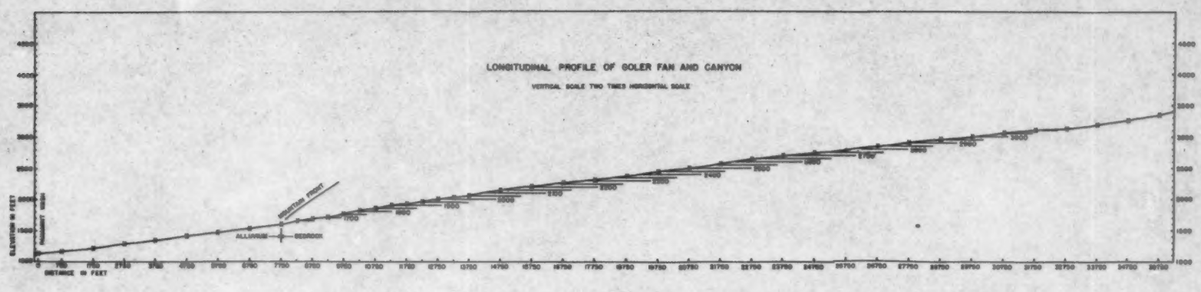
Goler Canyon

Goler Canyon, whose longitudinal profile is shown in Plate 8A, drains the area south of Manly Peak. It opens on the range front in a narrow V-shaped slot. The channel for 1000 feet back from the front is steep, narrow, and winding. It is cut in rather homogeneous intrusive rock, and the bedrock floor has a veneer of gravel and boulders. The bedrock is swept clean during each heavy run-off. Sometimes the quantity of debris dropped by the subsiding stream is not sufficient to form a road bed over channel irregularities. This portion of the road has occasionally remained impassable for several seasons.

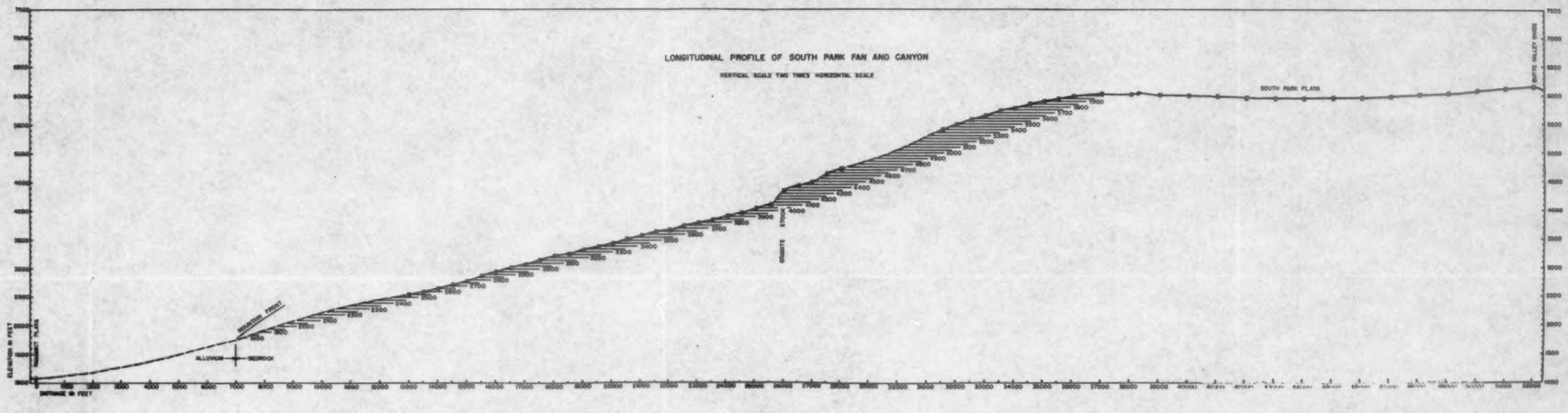
Most of the lower stretch of the valley is cut in rocks of the Panamint metamorphic complex, including dense black conglomeratic schists and quartzites. The convexities of profile do not seem attributable to local rock barriers. The profile as a whole from the front at 1400 feet elevation to the beginning of the headwater concavity at 3100 feet elevation is slightly convex. Several breaks in slope are superimposed on the general convexity. These are greater in vertical dimension and lesser in horizontal dimension near the front. A suggested interpretation of these relationships is based on the development of the range-front convexity by uplift, its upstream propagation, and the renewal at the front by repetition of uplift. The stream at the range front where steepened develops greater cutting power because higher velocity increases the energy imparted to the tools. As the channel is eroded more actively in the zone of steeper gradient this effect is gradually extended upstream. As it progresses upstream, the gradient in the downstream segment is reduced because the distance to the margin of the alluvial fan, which is the effective base level, remains constant.

If the erodability of the bedrock is much the same along a stream course such as Goler Canyon and the factors of load and run-off remain relatively constant the longitudinal profile is determined by the amounts of marginal uplift and length of intervals of stillstand. The long flat convexity suggests that uplifts occurred at successively shorter intervals which did not permit the adjustment in gradient to extend quite so far headward during each successive interval.

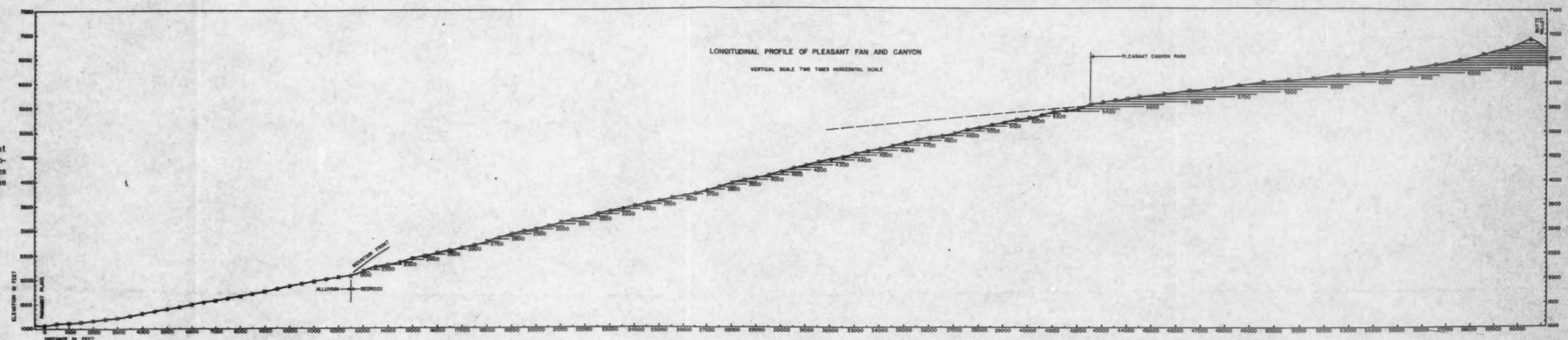
Many readers will see an analogy between the breaks in gradient of Goler Canyon and of other Panamint Range valleys and Penck's knickpoints. The differences in setting are (1) the comparatively small areal extent of the Panamint Range as compared with a huge domal upwarp, (2) the high relief of the Panamint Range as compared with the peneplain postulated for the initial stage by Penck, (3) the local generation of breaks in gradient at the range front instead of at some point along the stream course between a strongly eroding lower stream segment and a weaker eroding upper stream segment, and (4) the ungraded condition of Panamint streams as compared with the initially graded streams assumed by Penck (1924; 1925). Perhaps the principal common feature of the convexities of Panamint streams and Penck's theoretical knickpoints is the operation of accelerated uplift in both cases. Penck (1925, p. 89–90, quoted by Davis, 1932a, p. 402–403) conceives of the nick point as migrating upstream while its top serves as a local base level for the upper segment of the graded course. Continued acceleration of upheaval causes the production of a series of nicks all moving headward. Penck believed that nicks perpetuate their steeper gradient as they migrate upstream. The convexities of Goler Canyon and others of the Panamint front are progressively reduced as a higher gradient is extended upstream over a longer and longer segment of stream course. The strongest convexity of profile or nick is at the mountain front where it originates. Upstream the irregularities of profile become less and less pronounced. For this reason the writer does not consider that the profile convexities of Panamint streams are true knickpoints as defined by Penck. Many



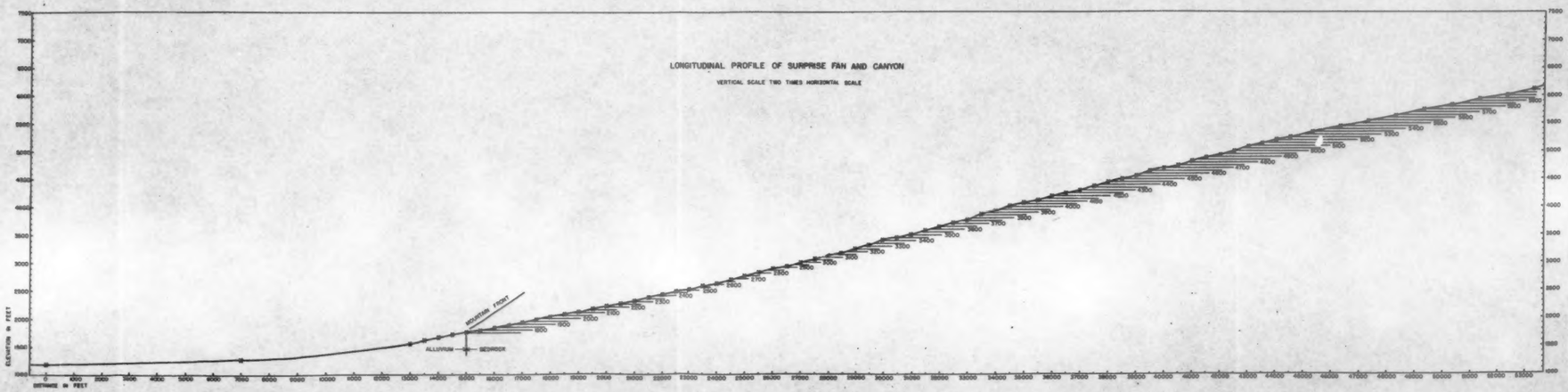
A. West-east longitudinal profile of Goler Fan and Canyon.



B. West-east longitudinal profile of South Park Fan and Canyon.



C. West-east longitudinal profile of Pleasant Fan and Canyon. The dashed line is a projection of the park profile which emphasizes the steeper gradient of the stream in the canyon below.



D. West-east longitudinal profile of Surprise Fan and Canyon.

PROFILES OF STREAMS ON WEST SIDE OF PANAMINT RANGE

American geologists are using the term nick point for breaks in stream gradient or convexities caused by structural control, although this usage does not conform to the original definition. Davis (1932a) has presented evidence to show that knickpoints as visualized by Penck cannot exist. If American geologists wish to adopt the term nick point for convexities in stream profile of any type or origin, it should be understood that the feature bears no relationship to the one conceived by Penck.

Redlands Canyon

No profile was constructed for Redlands Canyon, which is one of the most interesting canyons of the west flank. The writer has traversed this canyon several times on foot and has observed a more pronounced convexity of profile in the lower course than that in Goler Canyon to the south. A fall near the canyon mouth represents a vertical offset of 200 feet in the stream channel. An initial fall may have been formed by displacement, but the present position and height of the fall depends on recession in a brecciated quartzite zone from the range front. Above the fall the gradient of the channel is 6°. Farther upstream is a stretch of channel with a gradient of 13°, which indicates a second convexity in course. At several places falls 1 to 10 feet high occur in the channel, but these are caused by aplite dikes cutting the gneiss and quartzite of the channel. The general convexity of profile of the lower stretch of Redlands Canyon is not correlated with difficult erodability of the bedrock but with accelerated uplift of the range front.

South Park Canyon

The South Park Canyon longitudinal profile (Pl. 8B) is in many ways the most spectacular one in the Panamint Range. This canyon cuts across the steepest and highest part of the Panamint scarp. Its steep fan and lower canyon profiles may be attributed partly to this fact, partly to the relatively small size and eroding capacity of the stream itself. The lower canyon profile possesses convexities, suggesting an accelerated rate of uplift. At an elevation of 4150 feet there is a pronounced convexity caused by a massive granite stock. Above this the course rises steeply to an elevation of 6030 feet where it drops off easterly to a small playa at 6020 feet, from which playa it rises a few feet in a quarter of a mile and again drops off to the east in South Park playa at 5955 feet elevation. This reversal in the headwaters profile has been attributed in this paper to reversal in gradient produced by rotation of the range.

Pleasant Canyon

The Pleasant Canyon profile (Pl. 8C) shows a pronounced convexity back of the mountain front and several smaller ones upstream. The canyon is cut in the Panamint metamorphic complex, and the convexities could not be correlated with more difficult erodability of the bedrock. A short distance above the Worldbeater Mine (4390 feet on the profile) the canyon cuts the Worldbeater granite porphyry (Murphy, 1932, Pl. IV), yet the profile shows no irregularity here. The rather rectilinear canyon profile is interpreted as reflecting uniformly spaced intervals of uplift and rest. A break in gradient at 5500 feet elevation is interpreted as the farthest upstream effect of rejuvenation during the period of upfaulting.

Surprise Canyon

The Surprise Canyon profile (Pl. 8D) does not reach the head of the canyon, hence it does not show the concave headwater profile. Up to an elevation of approximately 5600 feet as represented on the profile the canyon is cut in rocks of the Panamint metamorphic complex. Above that and to a point beyond the old Panamint City smelter (6020 feet elevation on the profile) it is cut in the Marvel dolomitic limestone and Surprise formation (Murphy, 1932, Pl. IV). However, no irregularity of profile is seen. A falls in dolomitic marble of the complex occurs at 2990 feet elevation, but this local irregularity has no expression on the profile. No great convexity exists back of the front, and the lower canyon stretch as a whole is slightly concave. This is interpreted as reflecting a long enough standstill for extensive adjustment of gradient. The most recent upfault-

ing would be considered older than that along the range front farther south.

Since this conclusion is based on time required for establishment of concavity of profile streams of similar discharge flowing through areas of rock of similar erodability must be compared. Small streams may retain convex profiles throughout the time required for large streams to reach concavity of profile. Surprise Creek and Pleasant Creek to the south are of comparable size, and both flow through rocks of the Panamint metamorphic complex in their lower courses.

Wildrose Canyon

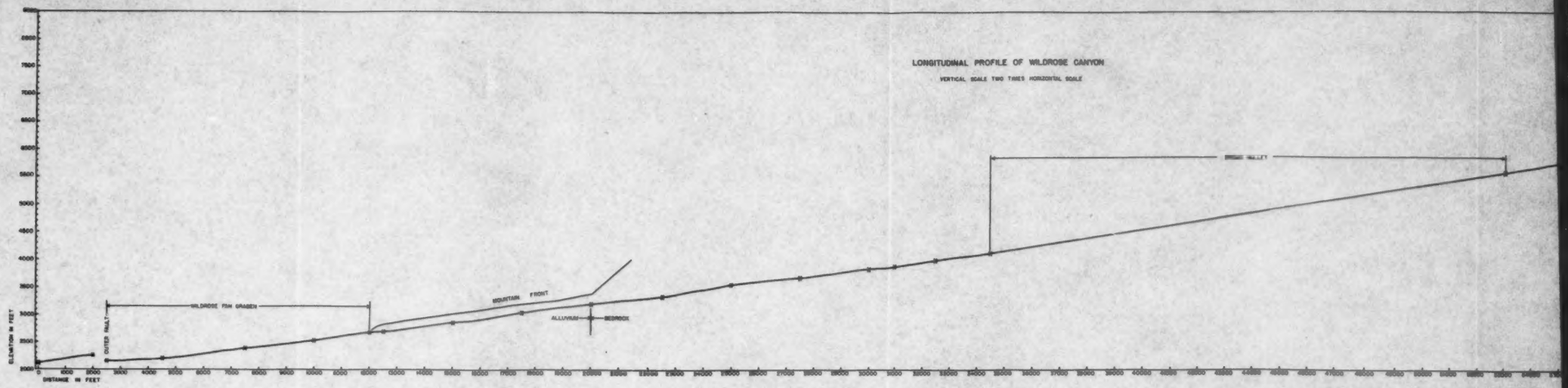
The Wildrose Canyon profile (Pl. 9A) shows a much more gentle gradient than that of other canyons farther south on the western Panamint flank. As a whole, it approaches the concave upward profile characteristic of an undisturbed stream. The broad valley segment fits smoothly into the profile. It suggests that major upfaulting of this part of the front is older than that to the south. However, the lower course is cut in Tertiary fanglomerates which are more easily erodable than the metamorphics. The time required for establishment of concavity of profile is less than that in the case of streams to the south, and comparison is difficult.

Valley Profiles of the Eastern Panamint Flank and Dissected Fans of the West Side of Death Valley

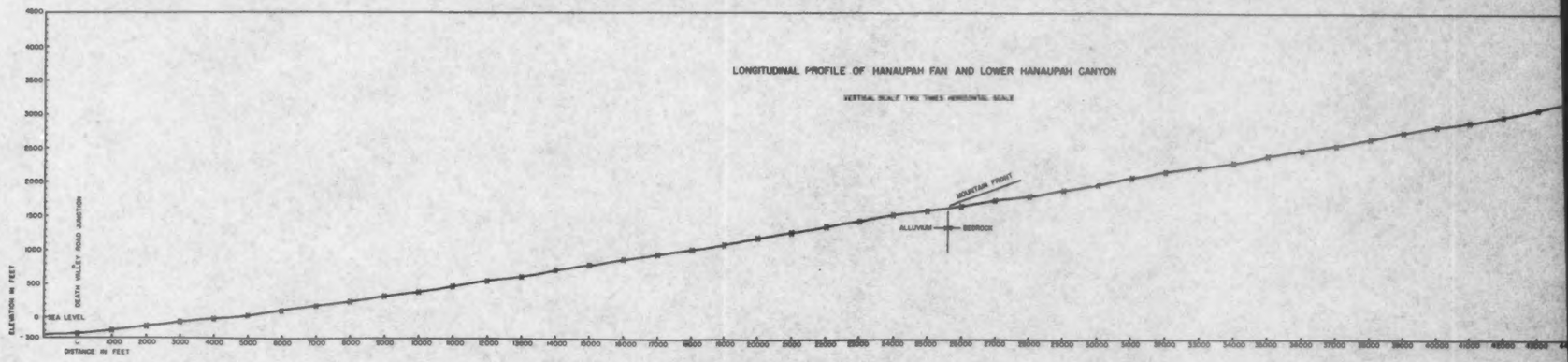
Hanaupah Canyon.—Hanaupah Canyon (Pl. 6, fig. 2), near the middle of the east front of the Panamint Range, is typical of others to the north and south. The profile of lower Hanaupah Canyon (Pl. 9B) is remarkably rectilinear and shows no point of inflection near the mountain front. It suggests that the gradient is in equilibrium with the other stream factors. This implies that the profile has not been disturbed by faulting for a long time. The gradient on the fan is in harmony with that in the canyon. This relationship should be expected if the load and discharge ratio remains constant. If there were large loss of water through percolation a steeper gradient would be required to transport the load. If part of the load were deposited there would be aggradation in the lower valley reaches. Percolation does occur as is shown by springs at the fan tips around Death Valley playa, and aggradation is shown by embayment of canyons.

The Hanaupah fan is trenched in its apical portion. The trench is 50 feet deep near the canyon mouth and diminishes in depth down the fan until it disappears about half way down to the fan tip. At this point distributaries diverge from the trench and are constructing a new fan whose gradient is lower than that of the old, dissected fan above. This relationship indicates an eastward rotation of the Death Valley piedmont formed by the coalescing dissected and reconstructed fans.

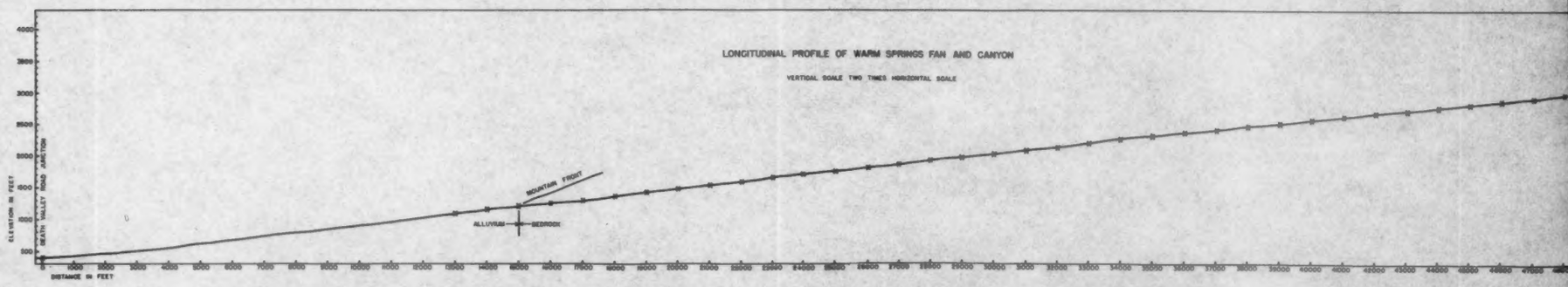
Warm Springs Canyon.—Warm Springs Canyon is a major canyon of the east flank of the Panamint Range. It is approximately 20 miles south of Hanaupah Canyon. The canyon profile (Pl. 9C) is nearly rectilinear throughout and shows no local disturbances. This profile, like those of Hanaupah and Wildrose canyons, seems characteristic of the intermediate and lower reaches of major streams where no recent large fault displacement has occurred. The nearly constant gradient implies a very delicate balance between load increase, fragment-size decrease, and water-volume increase down the course. Though these factors and also the gradient normally vary along the stream course special conditions may modify the normal relationship in Warm Springs Canyon. The headwaters which include part of Butte Valley covers an enormous area. Stream discharge is intermittent and occurs after rainfalls of cloudburst type concentrated on a few square miles of the watershed. Thus the stream is not progressively augmented in volume by tributary discharges. In many cases a full load is available in the cloudburst area. This results from extensive weathering and fragmentation of bare bedrock and mass movement of fragments into the stream courses during the long rainless intervals of the arid climate. If the stream becomes loaded in the small collecting area of heavy rainfall it can pick up additional load only as fragments are comminuted and transported with less expenditure of energy. Long stretches of nearly uniform gradient in the master stream course could be built and maintained



A. West-east longitudinal profile of Wildrose Canyon.

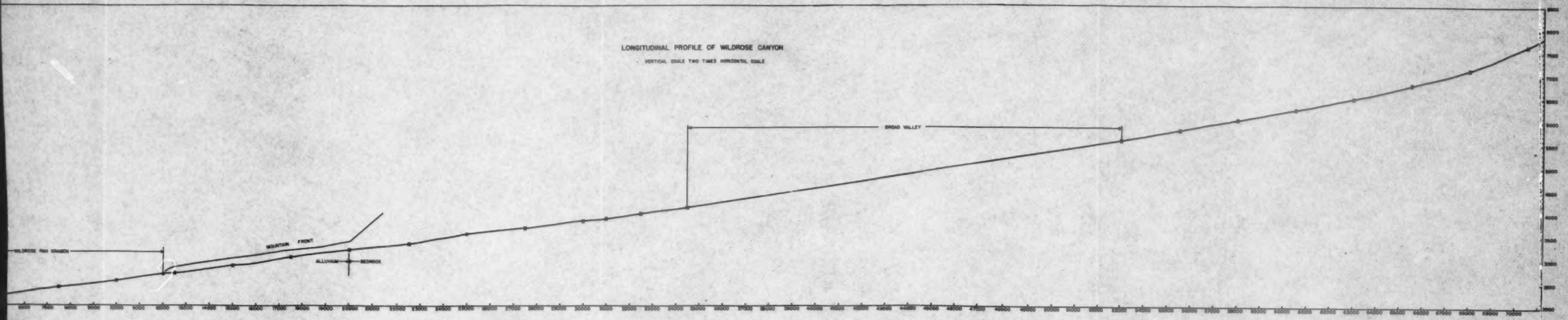


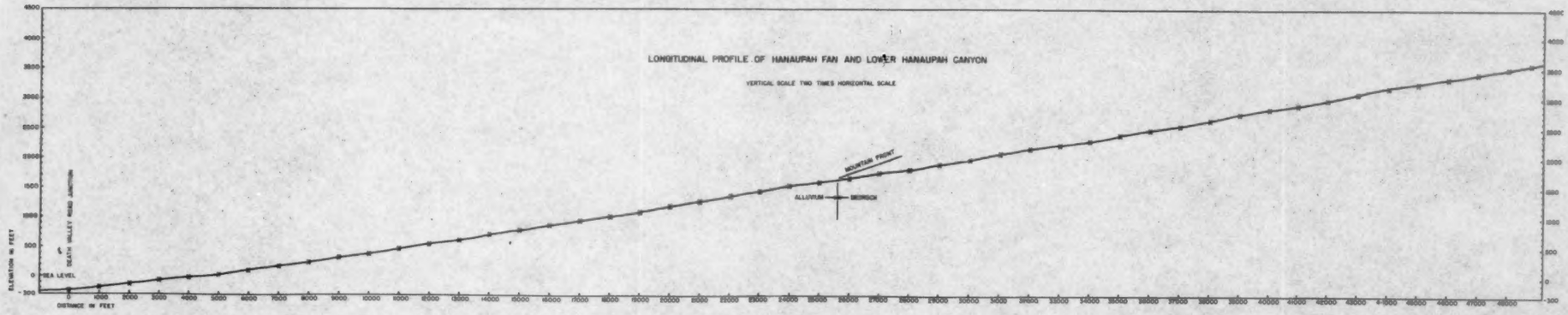
B. East-west longitudinal profile of Hanaupah Fan and lower Hanaupah Canyon.



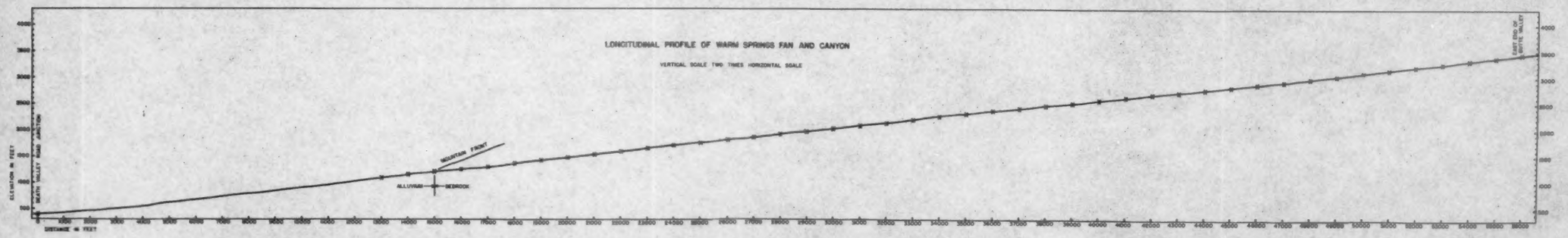
C. East-west longitudinal profile of Warm Springs Fan and Canyon.

WILDROSE CANYON PROFILE OF WEST SLOPE AND PROFILES OF STREAMS ON EAST SIDE OF PANAMINT RANGE





linal profile of Hanau-
anaupah Canyon.



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WILDROSE CANYON PROFILE OF WEST SLOPE AND PROFILES OF STREAMS ON EAST SIDE OF PANAMINT RANGE

by occasional floods wherein a large volume of water, virtually fully loaded, flows from headwaters to fan.

The Warm Springs fan is dissected in a manner similar to the Hanaupah fan. However, a well-developed terrace below the old fan surface and above the channel in the entrenched segment of the fan indicates recent tilting in two epochs separated by a brief period of standstill.

Rotation of the Panamint-Death Valley Blocks Together

Davis (1925, p. 391) postulated eastward rotation of the Panamint block because of the fresh uplift of its western front, the furrowing of detrital deposits on its eastern slope, and fresh downfaulting against the Amargosa Range (Black Mountains) to the east. Later a combined eastward tilting of the Panamint Mountains block and the Death Valley block was suggested (Davis and Maxson, 1935, p. 339). Not only do the fresh scarps of the west fronts of the Panamint Mountains and the Black Mountains with playas hugging their bases testify to this movement but also the evidence introduced in preceding paragraphs. The stream valleys both in cross profile and longitudinal profile record successive stages of uplift of the Panamint west front. The stream valleys of the east front of the Panamint Range do not register any recent disturbance between the range and Death Valley. Entrenchment of fans shows eastward tilt of the Death Valley block which is thus associated closely with the Panamint block in recent rotational displacement.

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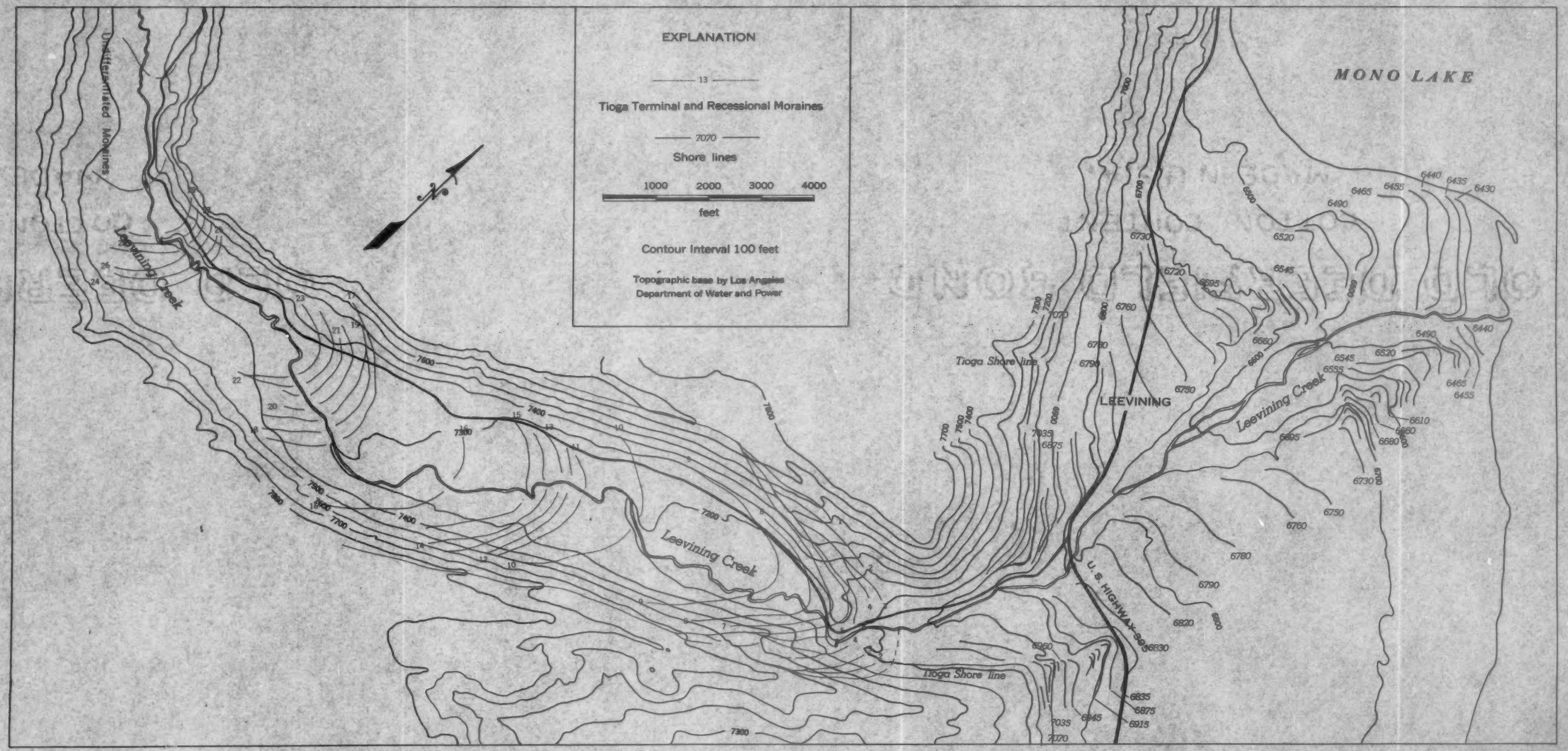

TIOGA MORAINES AND LAKE RUSSELL SHORE LINES AT LEEVINING CANYON

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MORAINE AND SHORELINE RELATIONSHIPS AT MONO LAKE, CALIFORNIA

BY WILLIAM C. PUTNAM

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ABSTRACT

Sierran glaciers reached Lake Russell in the late Pleistocene, and shore lines cut in lateral moraines of the next-to-last glacial stage (Tahoe) extend into troughs vacated by the ice at the close of that stage. During the waning phase of the last glacial stage (Tioga) conspicuous shore lines were carved on slopes bordering present Mono Lake. Terminal moraines of the Tioga stage, nested inside moraines of the preceding advance, reach the uppermost shore lines of Mono Lake and appear to be contemporaneous with its last expansion. Both the Tioga terminal and recessional moraines show that ice retreat was pulsatory, with several relatively long halts interrupting times of rapid recession. The comparatively stationary ice fronts probably can be correlated with broader lake terraces, the rapid ice withdrawals with narrower terraces.

INTRODUCTION

General Statement

Mono Lake, a permanent lake in the Great Basin, was much larger during the late Pleistocene, as shown by shore lines carved on slopes surrounding the present lake. At the mouths of canyons on the eastern slope of the Sierra Nevada, shore lines of this expanded lake—Lake Russell—cut moraines of the next-to-last glacial stage (Tahoe). Deltas built by glacial streams of the last stage (Tioga) merge with upper lake shore lines in three of the four glacial canyons marginal to the lake.

This paper, concerned with the record of the waning phase of the last glaciation, correlates terminal and recessional moraines of the Tioga glaciers with shore lines left by the receding lake. The record of earlier fluctuations of the lake has been destroyed by its later expansions, although there are a few traces of a higher shore line which has been assigned to the Tahoe stage (Putnam, 1949, p. 1295).

Regional Setting

Mono Lake, with a surface area of 85 square miles, is about 350 miles north of Los Angeles and 180 miles east of San Francisco (Fig. 1).

The lake has no outlet, and as a result its water is charged with soluble salts, chiefly Na_2CO_3 and NaCl. During the Tahoe stage, but not the Tioga, the lake had an outlet to the southeast and was connected with Owens Valley

FIGURE 1.—INDEX MAP

and thence to Death Valley. The poorly preserved Tahoe shore line is at an altitude of about 7180 feet, while the sharply defined, and therefore more accurately located, Tioga shore line is at an altitude of 7070 feet.

The bold eastern escarpment of the Sierra Nevada forms the western boundary of the lake today (Fig. 2), as well as at the time of its maximum expansion. This eastern slope is regularly steep, with an average of 26°–27° west of Leevining. The escarpment is not straight, but consists of a number of salients and re-entrants. This rectilinear pattern is controlled by faults cutting the Sierran bedrock which here consists of hornfels and plutonic rocks, chiefly quartz monzonite.

There were four ice advances in the Pleistocene glaciation of the eastern Sierra Nevada (from older to younger): Aeolian Buttes (Blackwelder's McGee stage), Sherwin, Tahoe, and Tioga. Only the last two are significant in this study. Till alone survives from the earlier glaciations, and glacial landforms have been removed by erosion or buried under volcanic material. The Tahoe glacial stage is represented by bulky lateral moraines; some are 850 feet high, 3 miles long, and 2500 feet broad at their base. In this area they universally extend as broad, sage-covered ridges beyond the Sierra Nevada out into the basin occupied by Mono Lake. Terminal moraines seem lacking for the Tahoe stage; they were eroded by meltwater supplied during recessional phases of this glaciation and by streams active during the succeeding Tioga advance.

Lateral and terminal moraines of the Tioga stage are nested inside the much larger Tahoe moraines. Since they are more recent, outlines generally are sharper, and all types, including lateral, medial, recessional, and terminal, are present. The distribution of these recessional and terminal moraines is the concern of this paper.

Previous Work

The pioneer work on the Mono Basin is the monographic investigation of I. C. Russell (1889). This is such a full and outstanding study that I have proposed the name Lake Russell for the Pleistocene forerunner of Mono Lake (Putnam, 1949, p. 1285), in honor of this pioneer geologist. Russell discussed all phases of the Quaternary history of the region—volcanic, glacial, and lacustrine. The complexity of the Pleistocene glacial sequence was not clearly understood at the time of his field work (1881–1883). Russell recognized multiple glaciation but did not study the relationships of the glacial and lacustrine record. Blackwelder (1931) recognized and named the four commonly accepted glacial stages in the eastern Sierra Nevada. He also pointed out that the last rise of the lake probably coincided with the Tioga glacial epoch (1931, p. 889). Kesseli (1948) attempted to correlate the late Pleistocene shore lines with the standard midwestern glacial sequence. I recently completed a study of the Quaternary history of the area (Putnam, 1949) but at that time did not study the more recent shore lines and moraines in detail.

Present Investigation

Field work on the present project was carried on chiefly in the summer of 1947, supplemented by some work in the summer of 1948. Moraines were identified in the field, located on U. S. Forest Service aerial photographs, and plotted on a topographic map (scale 1:6000) made by the Los Angeles Department of Water and Power. Moraines were studied at Leevining Canyon, Grant Lake, and June Lake (Fig. 2).

Shore lines were also mapped on aerial photographs and their positions transferred to the same base map. Their altitudes were determined by telescopic alidade and stadia with the help of Mr. Paul Bateman of the Geological Survey, U. S. Department of the Interior, whose assistance is gratefully acknowledged. U. S. Coast and Geodetic Survey bench marks were used for primary control. Shoreline altitudes are probably accurate to ±5 feet; slope wash makes it difficult to locate the older shore lines more accurately.

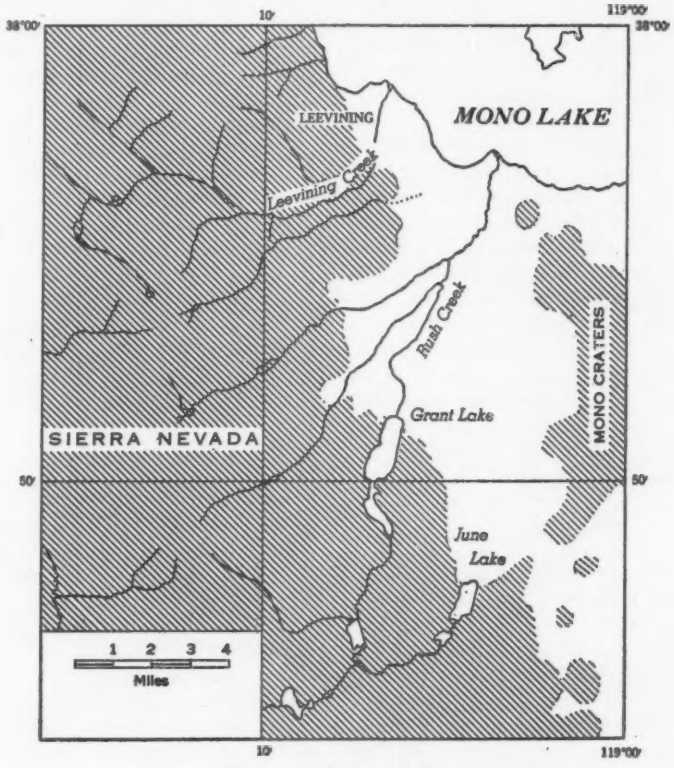


FIGURE 2.—LOCATION MAP

THE MORAINES

General Description

The Tioga terminal moraines are enclosed by much larger Tahoe lateral moraines. Tioga terminal moraines can be identified by their relative position, by their generally sharper crests, and greater frequency of boulders. Tioga recessional moraines occur either as isolated loops on the floors of glacial valleys or as clusters

of ridges that probably mark a relatively prolonged stand of the ice front.

Leevining Canyon

The Tioga terminal and recessional moraines are located on the accompanying map (Pl. 1); the set of profiles (Pl. 4) shows their relative heights. The terminal moraines make a cluster of eight and possibly nine morainal ridges. The outer limit of glaciation is more difficult to establish here than elsewhere, because the narrowness of the canyon has hastened the removal of earlier moraines by meltwater streams during later stages of glacial withdrawal. Also, three outer probable moraines extended below the 7070-foot shore line of Lake Russell and thus have been removed in part by wave erosion.

Although the record of terminal moraines is less full in Leevining Canyon than at the other two localities, the evidence of the recessional moraines is more satisfactory here because minor ones are not hidden by lakes or concealed by pumice as elsewhere.

Grant Lake

The Grant Lake terminal and recessional moraines are in the trough between two very large Tahoe lateral moraines (Pl. 2). Tioga terminal moraines are readily distinguished here because apparently no Tahoe recessional moraines have survived. The distinction between Tahoe and Tioga laterals is more difficult. However, the latter also seem more bouldery and sharp-crested, as at Leevining Canyon, and many of them can be followed into terminal and recessional moraines.

Tioga terminal moraines make 11 moderately well defined loops and form a pattern similar to that at Leevining: several low ridges are on the outside of the cluster, a group of higher ones are near the center, and a succession of lower ones are on the inside of the loop.

Recessional moraines also make a pattern similar to those of Leevining Canyon, but many of them are covered by Grant Lake and have to be inferred from the presence of lateral moraines that extend into the water. Larger ones project into the lake as paired capes. The most noteworthy set is the cluster of 10 that nearly divides the lake into two parts (Pl. 2). This group of moraines, judging from their size and position, appears comparable to the second cluster upstream from the terminal moraines in Leevining Canyon (Pl. 4).

The 7070-foot shore line of Lake Russell probably just reached the Tioga terminal moraine. It certainly extended well into the embayment between the Tahoe lateral moraines and cut shore lines on their slopes. Outwash from the Tioga glacier built a 3500-foot delta into this embayment during the high stand of the lake; the average surface of this delta is at 7060 feet (Pl. 2). The foreset slope is still largely intact, at an approximate angle of 20°. Rush Creek has incised a postglacial, 70-foot canyon into this delta. The delta appears to be approximately contemporaneous with the Tioga moraines. Slopes of the outer terminal moraines are graded to its surface, and the defile cut across the moraines by glacial meltwater is graded to the 7070-foot level.

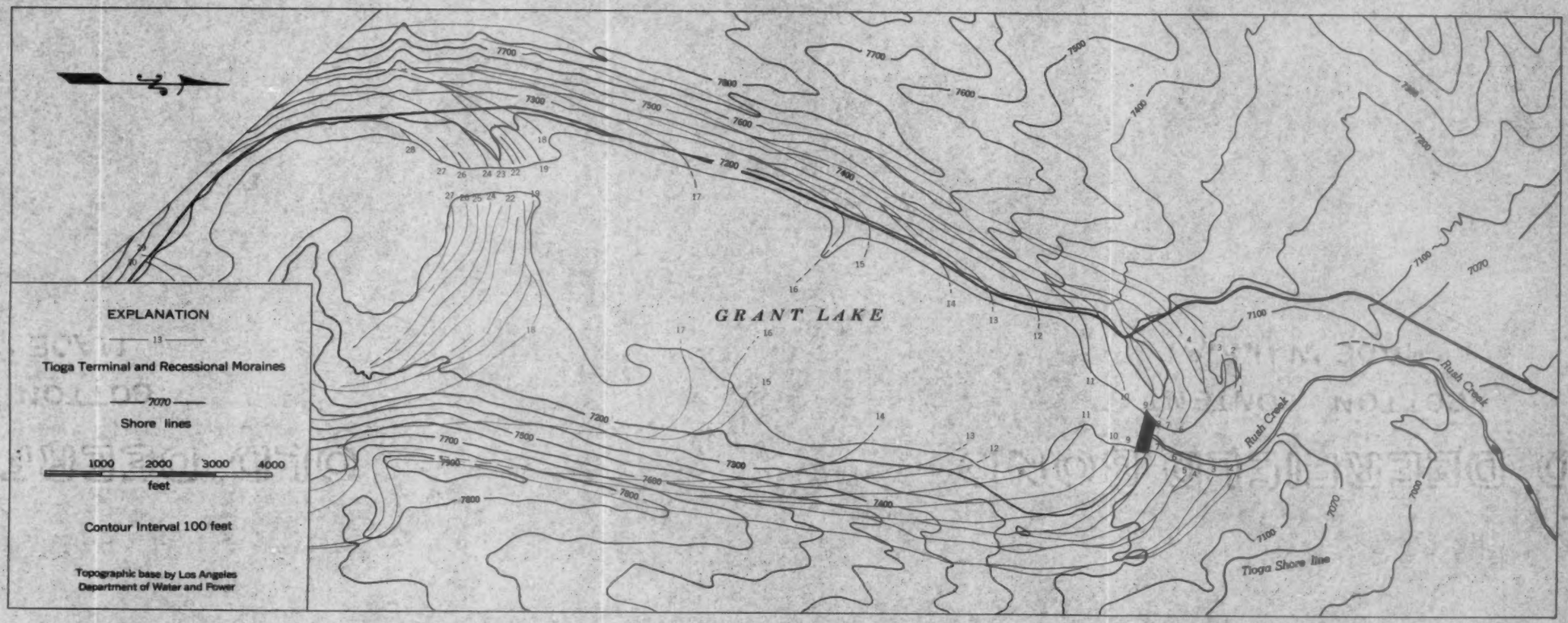
June Lake

Tioga moraines cover a wider area here than at other localities because the ice advanced as a broad, shallow lobe into rather open country (Pl. 3). June Lake has no natural outlet, although it had a spillway across the moraines in the late Pleistocene, and this overflow channel cut a defile 50 feet deep in tuff to reach Lake Russell 2 miles away.

A small basalt cinder cone and flow were erupted on the floor of the trough vacated by the Tahoe ice after its retreat and before the advance of the Tioga glacier. The cone, 2000 feet north of June Lake, and about half the flow were overrun by Tioga ice and are thus largely mantled by till.

Tioga moraines are more difficult to recognize here than elsewhere because they are lower and are covered by a blanket of pumice from the Mono Craters 2.5 miles northeast. Pumice may be 10 feet deep in depressions between moraines and has buried minor irregularities.

The morainal pattern is generally similar to other canyons (Pl. 3). Here there is an outer cluster of eight or nine terminal moraines followed by a broad expanse with two lesser groups of recessional moraines (six moraines) and then a secondary maximum of eight fair-sized moraines between the cinder cone and the lake.



TIOGA MORAINES AT GRANT LAKE

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The group adjacent to the lake seems equivalent to the set that nearly divides Grant Lake into two parts, and to the second set of moraines in Leevining Canyon (Pl. 4).

Lake Russell Shore Lines

General Characteristics

Late Pleistocene and Recent shore lines of Lake Russell were mapped near the mouth of Leevining Canyon, and their distribution is mapped with the Leevining moraines (Pl. 1).

Thirty-eight shore lines were identified on the west margin of Lake Russell. Some have broad treads, while others are little more than water marks (Pl. 4). Doubtless, quite a number of strand lines in the latter category have been overlooked, for wash from upper benches conceals details on lower benches. This burial makes determination of the altitude of former shore lines difficult, but a limit of ±5 feet is considered valid.

Lake terraces above the level of Leevining (6790 feet) are cut in Sierran bedrock, alluvial cones, or Tahoe lateral moraines. Below Leevining they are cut in lake deposits, chiefly silt. Gravel layers occur locally; there are five at Rush Creek where the lake-bed section is at least 160 feet thick. These gravel beds may record lower lake levels but they may also mark proximity to a stream mouth.

The exact age of the lake beds has not been determined; the lower ones may be equivalent to the Tahoe glacial stage, while the upper beds very likely are Tioga in age. The broad bench on which Leevining stands appears to be the surface of a delta built into Lake Russell during a period of relatively stationary lake level. The foreset beds of this delta, exposed in a ravine about 1 mile north of Leevining, dip 20°. Terraces below the Leevining level are cut in these foreset beds.

The profile (Pl. 4) shows that the lake level probably was not lowered at a constant rate, but that periods of relative stability were followed by times of rapid fall. Reversals probably also occurred, to judge from the history of Mono Lake during the past 70 years. Lake levels have been recorded with present-day accuracy only since 1912, and their changes are indicated on Figure 3, based on data published

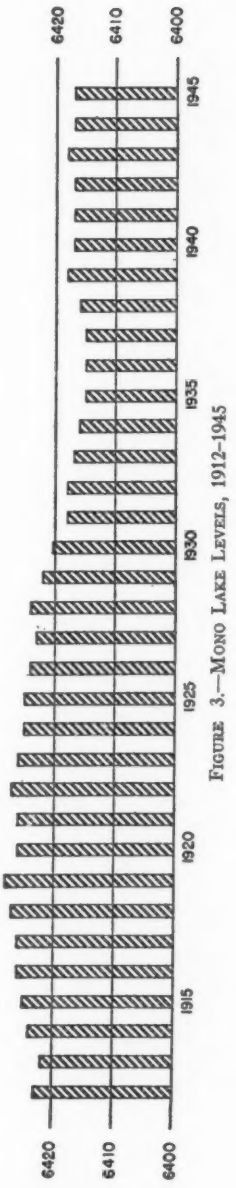


Figure 3.—Mono Lake Levels, 1912–1945

by the U. S. Geological Survey (1934, *et. seq.*). The altitude of the lake now (May, 1948) is 6415 feet, but it reached a maximum of 6428 feet in 1919, a drop of 13 feet in 29 years.

Questionable evidence indicates that the lake level rose rather steadily during the latter part of the nineteenth and early part of the twentieth centuries. According to I. C. Russell (1889, p. 298) at the time of his visits in 1881–1883:

> "Lake Mono, like all inclosed water bodies, is subject to changes of level, dependent on alternations of seasons and on secular climatic oscillations. . . . During the past twenty or twenty-five years it is thought by some to have risen as much as fifteen or twenty feet. . . ."

Willis T. Lee (1906, p. 23) saw the lake in 1904 and reported that trees and shrubs standing in lake water indicated a recent rise of lake level. According to him, the water level in 1898 was 6412 feet, 19 feet higher than in 1883. This and other fragmentary evidence suggests a rise of the lake surface of about 35 feet from 1883 to 1919. Since 1850 the lake may have risen 40 or 50 feet.

Antevs (1939) states that

> "Mono Lake rose 50 feet between 1857 and 1919 [Harding, 1935]. In 1914 it drowned and killed an 150-year old tree thus demonstrating that it had reached higher than since prior to 1750 [Huntington, 1917]. After maintaining a nearly unchanged level for some years, the lake subsided because of the drought beginning in 1924. Mono basin being closed, the fluctuations of the lake level, as Harding [1935] assumes, may largely be the result of varying inflow. . . ."

The lake has lost much of its value as a climatic indicator (1) through withdrawal of water from its tributaries for irrigation within the basin, and (2) through removal of water by the aqueduct system of Los Angeles. Diversion of Mono Basin water to the Owens River started in July 1941. Today, throughout much of the year, only minor amounts of runoff reach the lake.

The map (Pl. 1) and profile (Pl. 4) show that the older shore lines can be separated into an upper series of closely spaced, narrow benches from 7070 to 6875 feet, a middle series of broad treads separated by low risers and extending from 6830 to 6750 feet, and a lower series with closely spaced treads of intermediate width extending from 6730 feet to Mono Lake at 6415 feet. The upper series is cut in Sierran bedrock and alluvial fans west of Leevining Creek, on Tahoe lateral moraines east of the creek. The intermediate and lower series are cut in lake deposits which are part of the delta built into Lake Russell by Leevining Creek. The broad intermediate series approximately coincides with the delta surface. The lower series, at least between 6730 and 6455 feet, is cut in the delta front. Wave-cut benches crosscut foreset beds in several small ravines incised in the delta front west of Leevining Creek.

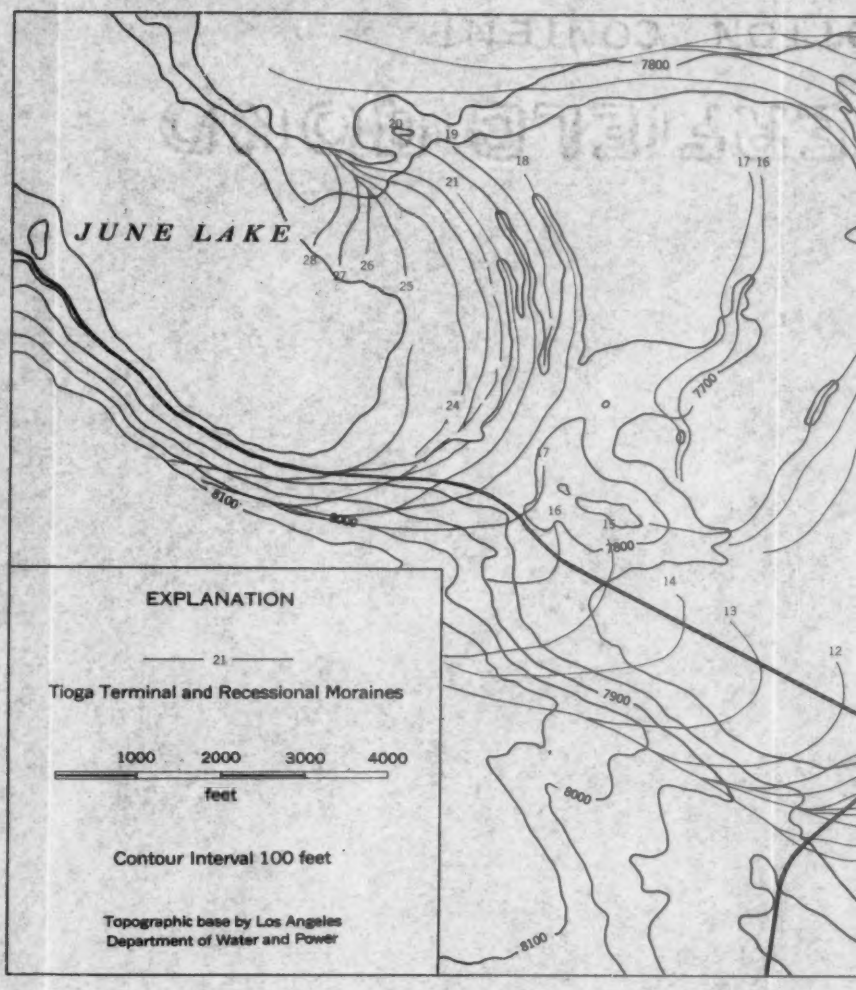
Leevining Creek has eroded a canyon to an average depth of 150 feet in its former deposits since the lowering of the lake level from the delta surface at 6830 feet. The stream has cut several sets of paired terraces along the canyon sides; these terraces have gradients comparable to the present stream. At the delta front they merge with wave-cut benches. Altitudes of lake terraces on either side of Leevining Creek increase toward the canyon, probably as a result of more rapid sedimentation near the stream mouth when it was depositing its load at the lake level represented by a particular terrace. In other words, the terraces here are the outer slopes of natural levees.

Correlation With Moraines

Their relation to Tioga terminal moraines and their degree of preservation indicate that the shore lines below 7070 feet are late Pleistocene to Recent.

The uppermost terraces merge with deltas built by meltwater streams in the canyons of Rush and Leevining creeks. These deltas and their associated terraces just reach the outer terminal moraines at Grant Lake and may crosscut the three outer terminal moraines at Leevining Canyon.

I believe the upper lake terraces from 7070 feet to perhaps 6940–6920 feet can be correlated with the prominent terminal moraines in each canyon; at Leevining Creek there are 8; at Grant Lake, 11; and at June Lake, 7. From the comparatively broad shoulder at 6940–6920 feet the terraces are little more than water marks until the wide surface of the 6800-foot bench is reached. This interval of narrow terraces probably can be correlated with the time of presumably rapid ice retreat shown (Pls. 1, 4) by the few, widely spaced recessional mo-



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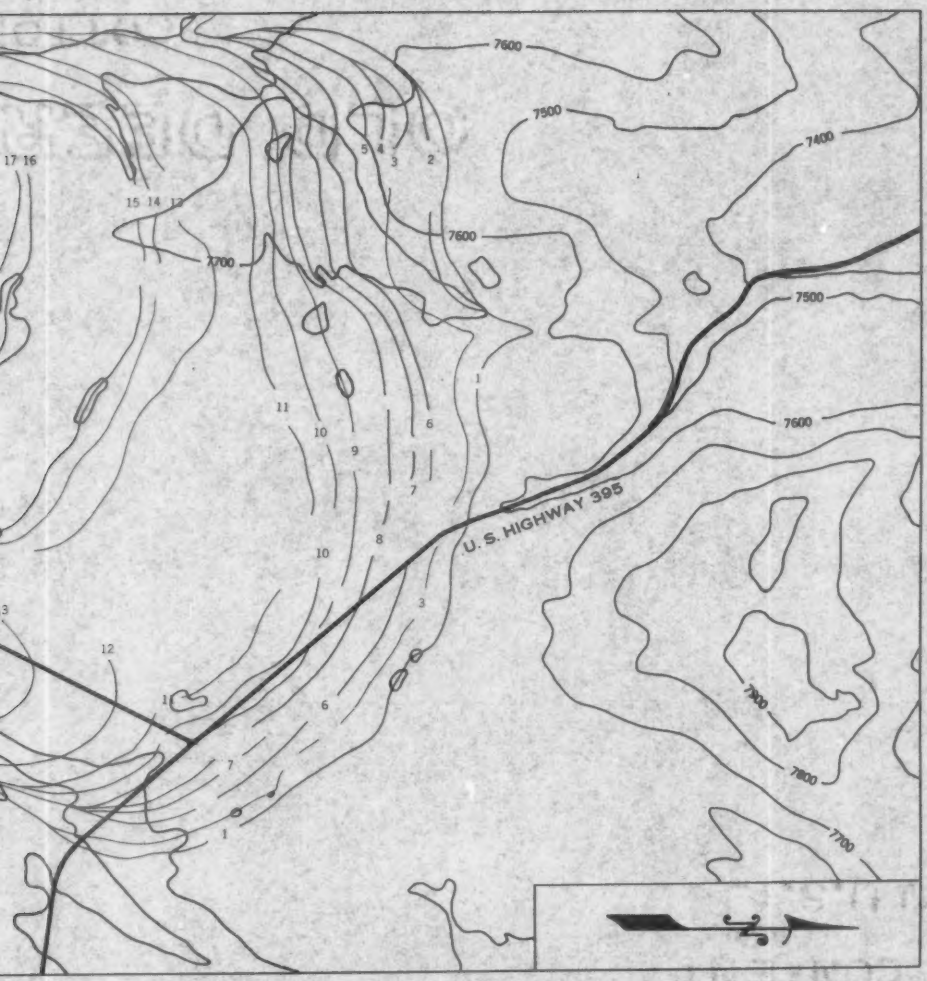

MORAINES AT JUNE LAKE

raines between the terminal moraines and the inner clusters that are linked together in the three profiles (Pl. 4). In this interval are seven moraines at Leevining Creek, six at Grant Lake, and six at June Lake.

The broad surface of the delta, from 6830 to 6750 feet, very likely can be correlated with the prominent inner morainal swarm shown on the maps of the three canyons and linked together on the profiles. The horizontal distance covered by these recessional moraines is roughly comparable with the terminal group. Their lower heights probably are a result of the reduced volume of ice at this stage in its retreat.

The vertical interval of the shore lines correlated with the terminal moraines is about 130 feet (7070–6940 feet) as compared with 80 feet (6830–6750 feet) for the recessional moraine cluster. If these correlations are valid, the smaller interval indicates a shorter time. This belief is supported by the fact that the volume of water in the lake was considerably reduced between the two stillstands. The lake had shrunk from a maximum width of 32 miles at the 7070-foot level to 19 miles at the 6800-foot stand. This means that the removal of an equal volume of water at the lower level would make a greater interval between shore lines than it would if the same amount evaporated at the high stand of the lake.

The greater width of the 6800-foot set of shore lines is explained by the fact that this shelf is in part the constructional surface of a delta and in part consists of terraces cut in lake deposits, here chiefly silt. Given an equal interval of time, and equality of wave action, these terraces would be wider than ones cut in Sierran bedrock, or even than benches cut in glacial till, for benches cut in the latter are quickly protected by a veneer of cobbles and boulders.

Terraces below 6730 feet, some of which are 300 feet broad, presumably can be correlated with recessional moraines upstream from the group that is linked together on the profiles. The upstream moraines are best displayed in Leevining Canyon, where two well-defined groups of low moraines are present (Pls. 1, 4). Individual moraines of the innermost set cannot be separated satisfactorily in the field; they are too low and densely forested to be distinguished.

No other moraines were mapped upstream from these, although some very low bouldery ridges were encountered. From about the midpoint of the glacial troughs to the cirques, glacial withdrawal presumably was rapid, and there were few prolonged halts. There are many small moraines in the upper reaches of each of the glacial canyons; for example they are conspicuous near the Tioga Pass entrance to Yosemite National Park, and these fresh-looking glacial deposits may be post-Pleistocene. According to Matthes (1942, p. 212–213):

> "The testimony of the moraines points to the same conclusion [as the desiccation of Owens Lake]. There is a notable absence of any gradational series of successively younger moraines leading from the Wisconsin moraines in the canyons below to the fresh-looking modern moraines that lie close to the ice fronts, and there is nothing to suggest that these modern moraines were formed merely by the last of a long series of recessional stages of the glaciers. They form an entirely separate group of very recent origin. Their volume of rock waste, moreover, is too small to represent an accumulation of 10,000 years or more. There is thus, on this score also, good reason to believe that the present glaciers of the Sierra Nevada, like the modern Owens Lake, are creatures of the cooler and more snowy period that followed the 'climatic optimum.' They are successors to, rather than remnants of, the large glaciers of the Pleistocene Epoch, and their age is presumably about the same as that of the present Owens Lake—that is, about 4,000 years."

Doubtless the lower shore lines record these minor oscillations of high-Sierran glaciers and snowfields. Shore lines cut during a small rise of the lake cannot be distinguished from those carved during a lowering of the water surface. The closely spaced, fresh-looking shore lines—little more than water marks—between 6440 feet and the present lake at 6415 feet probably reflect these oscillations of Recent climate.

Summary and Conclusions

Prominent shore lines bordering Mono Lake that reach a height of 655 feet above the present water surface were cut in Late Pleistocene (Tioga) and Recent time by Lake Russell.

The field evidence indicates that the high stand of the lake was essentially synchronous with the maximum advance of Tioga ice, and that, as the ice withdrew, the lake level was accordingly lowered. When the ice front was relatively stationary, the lake waves cut broad terraces; when retreat was rapid, only narrow benches were carved. The broad bench at

6850–6730 feet, on which the town of Leevining stands, marks a relatively prolonged halt in ice withdrawal.

The belief that the maximum rise of the lake coincides with the peak of late Pleistocene glaciation disagrees with Simpson's (1934, p. 460) position that glacial and pluvial stages are noncoincident at Lakes Russell and Bonneville.

Pluvial stages may mark interglacial times in such regions as Africa, far beyond the immediate effects of glaciation, but it seems unlikely in an area such as this in which glaciers actually reached lake level. An expectable consequence of glaciation in the Sierra Nevada presumably would be an increase in precipitation over immediately adjacent regions, as well as an increase in runoff from meltwater. This would be expressed in a closed basin at the foot of a snow-covered and strongly glaciated mountain range, such as the Sierra Nevada, by a rise in lake level. Conversely, with a reduction in snowfall and a decrease in runoff, the lake level would fall.

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University of California, Los Angeles 24, Calif.

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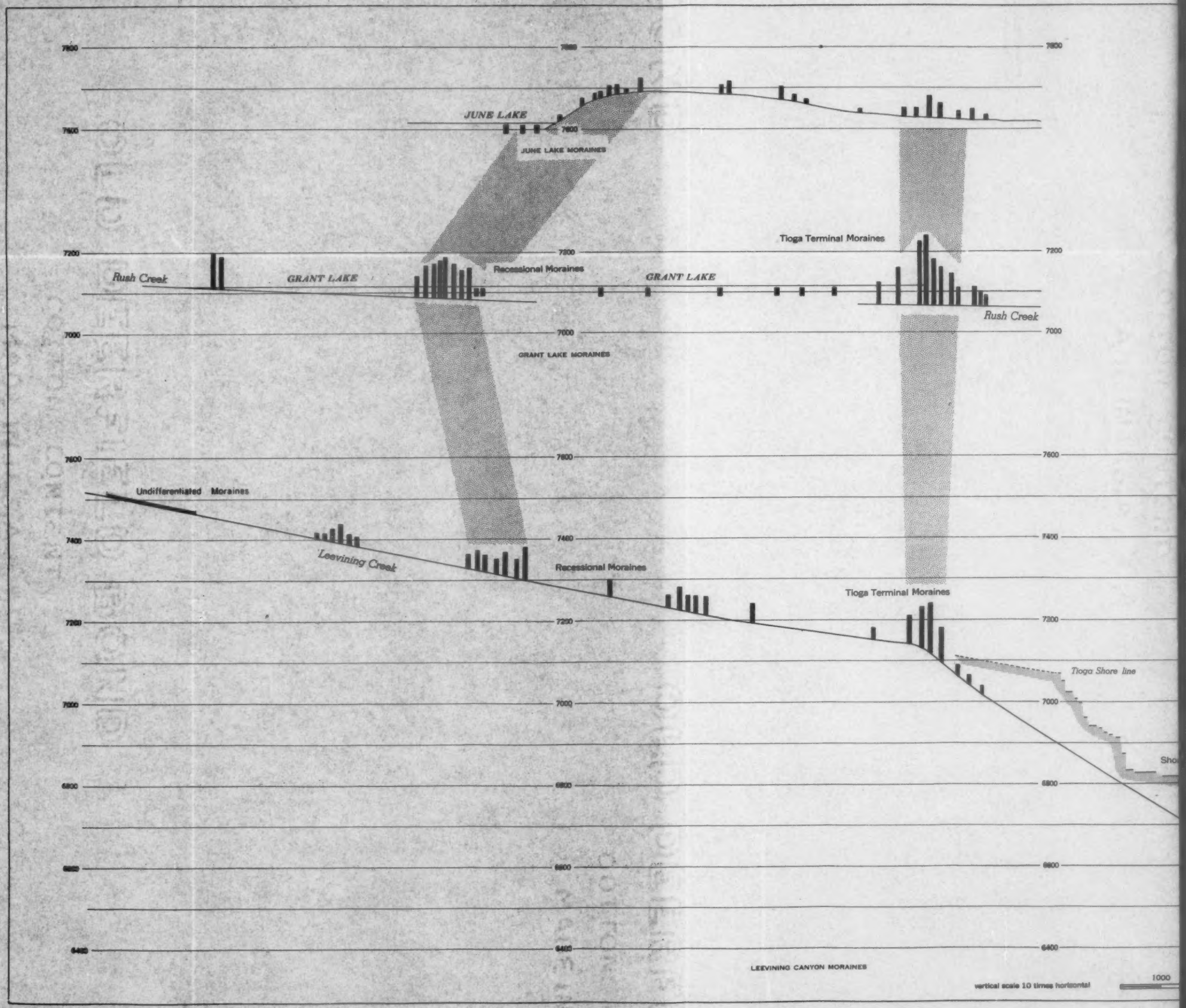
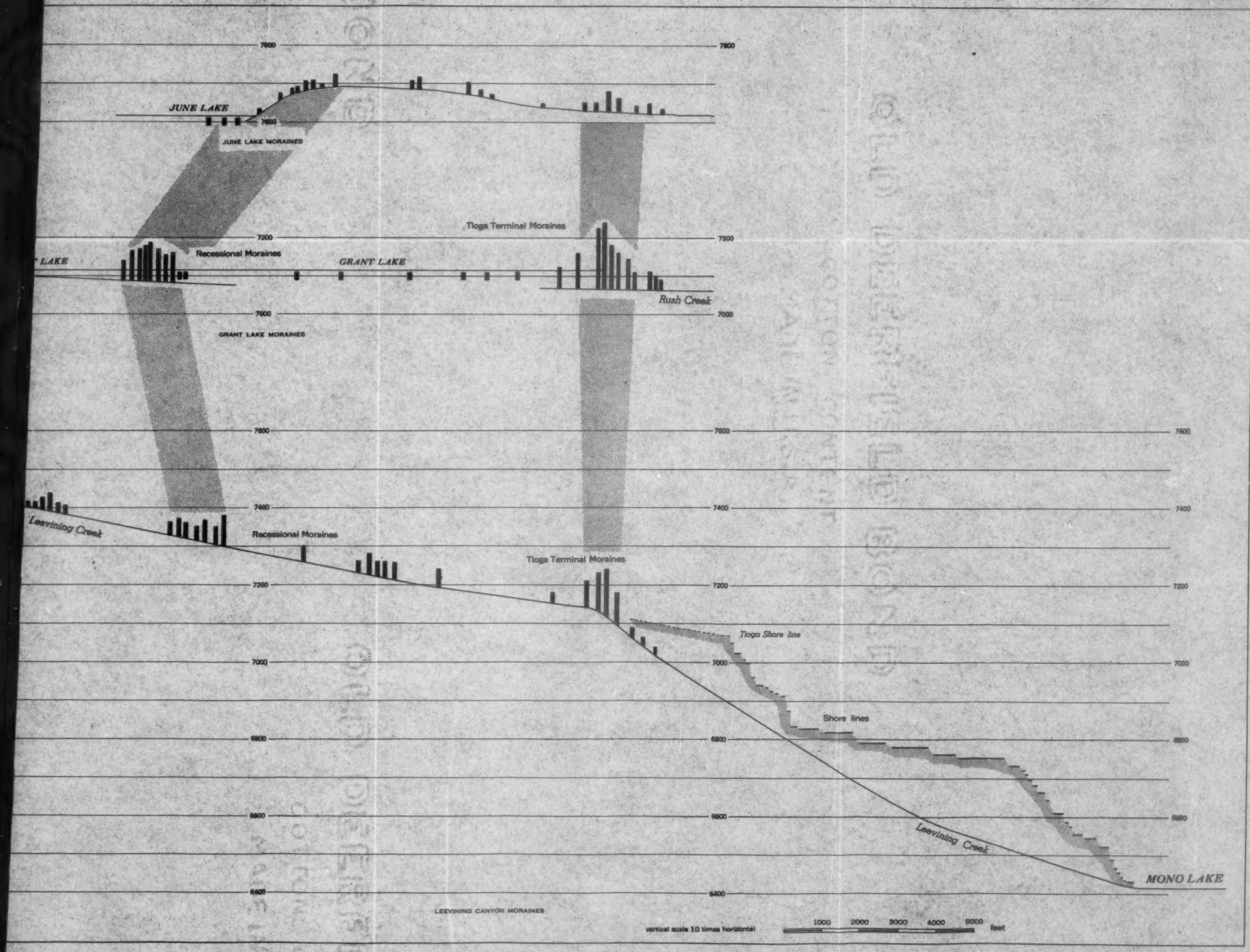


PROFILES OF TIOGA MORAINES AND LAKE RUSSELL SHORE LINES



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BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
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GOLD AND SILVER CONTENT OF SOME TREES AND HORSETAILS IN BRITISH COLUMBIA

BY HARRY V. WARREN AND ROBERT E. DELAVAULT

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ABSTRACT

An area known to contain many gold-bearing veinlets, and in which many prospect pits and trenches had been dug, was selected for this investigation. Overburden usually ranging from 4 to 8 feet in depth, and in part composed of glacial clay, wherever panned near bedrock revealed the presence of gold. The amount of gold yielded by panning surface material was in most cases negligible.

Samples from five species of trees were carefully taken in a manner that appeared to eliminate danger of physical salting. Four collections of horsetails were also made from near-by ground which was, however, known to contain much more modest quantities of gold.

Careful analyses revealed gold in every sample but one. Control samples from non-gold-bearing areas with similar climate in no instance provided weighable quantities of gold.

Silver was found in most plants including those growing in areas where there was no evidence of silver mineralization.

INTRODUCTION

During the past 15 years the senior author has spent considerable time prospecting. During the past 4 years we have been carrying out some biogeochemical researches at the University of British Columbia. Since 1946, when our first biogeochemical results were presented to the Geological Section of the Royal Society of Canada, we have been asked by many persons if we expected eventually to recover gold from our forests. The following results show that in places our forests, like the oceans, do contain measurable amounts of gold and silver. However, our forests, like the oceans, are not liable in the foreseeable future to be exploited commercially for their content of gold and silver.

This jesting from our friends served a useful purpose. It caused us to realize that we had at our disposal an area ideally suited to investigations of the gold content of some of our common species of trees and lesser plants.

We present the results of an investigation which was initiated with considerable scepticism. Our results are interesting, but other workers must duplicate them before they can be accepted generally.

ACKNOWLEDGMENTS

The authors were assisted by Rod Williams and Ruth Irish; Mr. Williams was responsible for the gold and silver assays. Mr. and Mrs. F. Brent rendered valuable assistance in collecting samples.

The authors are most grateful to The Geological Society of America for generous donations from the Penrose Bequest for this and other biogeochemical researches. These grants, together with smaller sums obtained from the Board of Governors, on the recommendation of the President's Committee on Research, largely through the efforts of Dean Daniel Buchanan and Professor M. Y. Williams, made these investigations possible.

Location and General Geology

The positive samples were collected from near the headwaters of the North Fork of Watson Bar Creek in the Clinton Mining Division of British Columbia. The area is about 6 miles west of Big Bar Ferry where a cable ferry is operated across the Fraser River. A pack trail some 10 miles long leads from Big Bar Ferry to the headwaters of the North Fork of Watson Bar Creek. The samples were taken at elevations ranging from 6000 to 6200 feet above sea level.

The geology of the area is in general simple. A series of gently dipping tuffs, breccias, and sediments, all of unknown age, are cut by numerous porphyry dykes and at least two other minor intrusive bodies which approximate quartz diorite.

All the rocks are cut by several steeply dipping shear zones. Intersecting these shear zones at approximately 60-degree angles and cutting the sediments are numerous narrow but persistent veinlets, seldom more than an inch wide, but most rock adjacent to them is bleached for a distance of from half an inch to an inch on either side. As there are no rock outcrops in the area, information about these veinlets has been obtained only by trenching, pitting, and groundsluicing. Considering their width, the veinlets seem reasonably persistent; they were followed in six places for 20–30 feet before being lost beneath overburden. At least twelve have been exposed within a distance of about 300 feet at right angles to their strike. They are known to extend over a vertical range of at least 800 feet. They consist largely of quartz abundantly stained with limonite, with minor amounts of pyrite, galena, and in some places conspicuous native gold. The relatively rare bismuth silver telluride, wehrlite, has been found in these veins. Dr. R. M. Thompson confirmed the identity of the wehrlite by an X-ray powder photograph. These veinlets have been so weathered that the mineralogy of unaltered vein matter is not yet known. Another set of veins striking so that they cut or are cut by both shear zones and veinlets was uncovered in 1948. These veins consist largely of carbonate, are from 1 to 2 feet wide and have dips ranging from 25° to 40°. Their relationship to the shear zones and to the veinlets is unknown. Where uncovered, they are deeply weathered and heavily iron-stained. A few samples containing some unweathered vein matter have revealed the presence of small amounts, probably less than 1 per cent, of metallic minerals. Minerals identified are: galena, chalcopyrite, tetrahedrite, and wehrlite; Dr. R. M. Thompson identified the last two by X-ray powder photographs.

Much of the area below the 6200-foot level is drift-covered, and in most places where the sections of the drift have been removed a false bedrock of glacial clay or hard pan lies immediately on bedrock. This layer of glacial material generally ranges from an inch to a foot thick, and its removal is a task exasperating in the extreme. Only a few bits have been sunk to bedrock above the 6200-foot level. However, information from these bits suggests that, although glacial material occurs above this level, glacial clay is lacking. In the creek below where these veins have been found, some $250,000 of coarse placer gold, remarkable for its low silver content, has been recovered. This area has been prospected in an effort to discover the source of this placer gold.

In order to explore the area with the least possible effort a dam was built on the upper creek, and a mile-long ditch was dug along the hillside. Cuts to bedrock were made from ditch to creek by groundsluicing aided by considerable pick and shovel work, the unaided water being, in many cases, unable to penetrate the glacial clay.

The area seemed ideal for our investigations. Trenching and pitting have revealed at least six gold veins within 300 feet of where the trees which were sampled were growing. Nevertheless, there were originally no outcrops in the immediate area, negligible gold near the surface, but some gold near the glacial "hard pan", usually under several feet of overburden. This gold may in part have originated from the weathering of veins above the 6200-foot level. The first quartz vein was discovered above the 6200-foot level by panning this gold. Beneath the seal of glacial "hard pan" there is more detrital gold. Five species of common trees were found within a few feet of each other, and comparisons in the gold content of each species would be valid.

TABLE 1.—GOLD ANALYSES

In parts per million (p.p.m.). Location of samples given in appendix

Positive Areas

Species	Per cent of ash in dry plant material	Gold content of ash†	Gold content of dry plant material
1. *Equisetum* sp.* (Horsetail)	16.70	.34	0.055
2. *Equisetum* sp.* (Horsetail)	17.20	.17	0.03
3. *Equisetum* sp.* (Horsetail)	18.00	.34	0.06
4. *Equisetum* sp.* (Horsetail)	22.75	.33	0.075
5. *Pseudotsuga taxifolia* (Douglas Fir)	2.30	.65	0.015
Juniperus communis (Dwarf Juniper)	3.25	.61	0.02
Pinus contorta (Lodgepole Pine)	1.90	nil	nil
Populus tremuloides (Aspen)	2.40	.89	0.02
Salix sp. (Willow)	2.20	1.02	0.023

Negative Areas

Species	% of ash in dry plant material	Gold content of ash (2)	Gold content of dry plant material
6. *Pseudotsuga taxifolia* (Douglas Fir) composite 12 samples	3.65	nil	nil
7. *Pseudotsuga taxifolia* (Douglas Fir) composite 5 samples	4.75	nil	nil
8. *Pseudotsuga taxifolia* (Douglas Fir) composite 5 samples	3.00	nil	nil
9. *Juniperus communis* (Dwarf Juniper) composite 4 samples	4.10	<0.03 estimate	<0.001
10. *Juniperus communis* (Dwarf Juniper) composite 4 samples	4.68	nil	nil
11. *Pinus contorta* (Lodgepole Pine) composite 3 samples	2.12	nil	nil
12. *Pinus contorta* (Lodgepole Pine) composite 2 samples	2.42	<0.03 estimate	<0.001
13. *Pinus ponderosa* (Yellow Pine) composite 5 samples	4.68	nil	nil
14. *Pinus ponderosa* (Yellow Pine) composite 5 samples	5.37	nil	nil
15. *Pinus ponderosa* (Yellow Pine) composite 10 samples	2.66	nil	nil
16. *Populus Tremuloides* (Aspen) composite 2 samples	7.14	0.03	0.0025
17. *Populus Tremuloides* (Aspen) composite 2 samples	6.90	nil	nil
18. *Salix* sp. (Willow) Kootenay	6.73	nil	nil
19. *Salix* sp. (Willow) Okanagan	6.00	nil	nil

* Species not determinable. Collected when no fertile stems could be observed.

† Estimated with reasonable accuracy to within 8 or 10 parts per hundred million on the 2 to 20 grams of ash used for fire assay. On the basis of controls a trace may be considered to be less than 3 parts per 100 million. Controls were run on 10 assay ton blanks to check the purity of reagents. The gold content of the samples was determined by actual weighing of gold beads.

All the horsetails were collected from earth-filled dams on the North Fork of Watson Bar Creek, between a quarter and half a mile from where the quartz veinlets occur.

Methods of Collection

More than normal care was taken to avoid all danger of salting. From the trees, only fresh new growth was cut, and this was taken higher from the ground than usual. This, of course, was not possible with *Juniperus communis*. First-year twigs and needles were collected from the conifers, and first-year twigs from the deciduous trees.

The horsetails presented a more difficult problem. To eliminate obvious factors which might cause salting we took four large samples from widely separated places and picked only the tops of fresh young growth. We took particular pains to avoid any area or plant which we thought had had any chance of physical contamination.

Methods of Analysis

We decided to employ ordinary fire-assay methods. Quite apart from the relative sensitivity of dithizone and fire assay methods, we felt that we would be far more convinced if we could offer gold and silver, and gold beads as evidence at the conclusion of our work. Every possible precaution was taken ro prevent salting, and ten assay ton control charges were run to be absolutely sure of the purity of the reagents. Tables 1 and 2 summarize our results. In default of a better term we have used "negative" to refer to an area where bedrock is well exposed and mineralization of the element being investigated is not present.

Table 1 suggests that under normal conditions some trees and lesser plants probably contain less than .001 p.p.m. which could be multiplied by number of samples in composites. Even if all the gold in the composite samples were from one of the constituent samples, the maximum amount present in any must be less than .005. Where gold is readily available, they may carry as much as .02 p.p.m. Horsetails, on the basis of somewhat scanty evidence, appear to carry from two to three times as much gold as the species of trees investigated.

As we were primarily interested in investigating gold, no attempt was made to obtain positive and negative samples for silver. However, as silver determinations have to be made at the same time as gold, 14 samples were run for silver. The results indicate that air-dried plant material from many trees and lesser plants usually carries between 0.1 and 0.5 p.p.m. of silver and that it may on occasion contain over 1 p.p.m.

Table 2.—Silver Analyses

Species	Per cent ash	Ag. p.p.m. ash	Ag. p.p.m. in dry plant material
5. *Pseudotsuga taxifolia*	2.30	17	0.39
5. *Juniperus communis*	3.25	8	0.26
5. *Pinus contorta*	1.90	nil	nil
5. *Populus tremuloides*	2.40	nil	nil
5. *Salix* sp.	2.20	1.3	0.28
4. *Equisetum* sp.	22.75	1	0.23
7. *Pseudotsuga taxifolia*—composite 5 samples	4.75	13	0.60
8. *Pseudotsuga taxifolia*—composite 5 samples	3.00	27	0.80
10. *Juniperus communis*—composite 4 samples	4.68	4	0.20
12. *Pinus contorta*—composite 2 samples	2.42	25	0.60
17. *Populus tremuloides*—composite 2 samples	6.90	1	0.10
19. *Salix* sp. Okanagan	6.00	3	0.20
13. *Pinus ponderosa*—composite 5 samples	4.68	30	1.40
14. *Pinus ponderosa*—composite 5 samples	5.37	4	0.20

The form or forms in which silver and/or gold may exist in a soil is unknown to us as is the manner by which they become available to a tree or lesser plant. However both originate in eruptive rocks (Goldschmidt, 1937); each ton of eruptive rock of the earth's crust contains on an average approximately 100 grams of copper, 40 grams of zinc, 0.1 gram of silver, and 0.005 gram of gold.

Goldschmidt (1935) reported on some of the trace elements which he found in coal ashes and noted that the concentrates of elements in these coal ashes ranged from 4 to 200 times

what they were in the average eruptive rock. Goldschmidt reported finding a maximum of 10 p.p.m. and an average of 2 p.p.m. of silver in "rich" ashes. No average gold content is mentioned, but a maximum figure of 0.5 p.p.m. in coal ash is cited.

If this evidence be accepted as a general guide, the results obtained by us are well within reasonable limits.

Little evidence is available on the occurrence of gold in trees and lesser plants. However Lundberg (1941) and Nemec (1935, 1936) and his associates (1936) have recorded scattered instances of such occurrences.

Conclusions

Trees and lesser plants growing in areas where there are good rock exposures and no silver mineralization of significance is known have been found to contain from 0.1 to 1.4 p.p.m. of silver. In negative gold areas, trees and lesser plants seldom carry as much as 0.0025 p.p.m. of gold and usually much less. However, above ground known to be auriferous, air-dried plant material contains as much as 0.07 p.p.m. of gold in horsetails and 0.02 p.p.m. of gold in some common trees.

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Appendix A

Samples Used for Analyses

6. Composite of Nos. 0:48, 1:48, 4:48–12:48 (inc.) and 14:48.
7. Composite of Nos. 2:48, and 4:48–7:48 (inc.).
8. Composite of Nos. 8:48–12:48 (inc.).
9. Composite of Nos. 8:48, 9:48, 12:48, 14:48.
10. Composite from same samples as #9.
11. Composite of Nos. 0:48, 10:48, 14:48.
12. Composite of Nos. 10:48, and 14:48.
13. Composite of Nos. 2:48–6:48 (inc.).
14. Composite of Nos. 7:48–11:48 (inc.).
15. Composite of Nos. 2:48–9:48 (inc.), 11:48, and 12:48.
16. Composite of Nos. 10:48, and 12:48.
17. Composite from same samples as #16.
18. Sample 12:46.
19. Sample 13:48.

Appendix B

Location of Samples

0:48. Summit of small ridge. Relatively free from glacial drift. On granodiorite. About half a mile south of Hope.

1:48. Summit of small ridge. Relatively free from drift. On schist. About 14 miles south of Siska.

2:48. On rocky talus slope with limited soil cover. On diorite to quartz diorite. No glacial drift noted. About 2½ north of Lytton.

3:48. On or close to summit of small nose. Considerable silt on Palaeozoic andesite. About 10 miles south of Ashcroft.

4:48. On slopes of small ridge at N.W. end of Yellow Lake. Some soil. On Cenozoic hornblende andesite. (Marron Formation)

5:48. On slopes of small ridge at N.E. end of Yellow Lake. Some soil. On Cenozoic andesite (Marron Formation).

6:48. On summit of small ridge about half a mile north of Okanagan Falls. On Cenozoic conglomerate. Some soil.

7:48. On slope on west side of Ellison Lake about half way down lake. On Mesozoic granodiorite and greiss. Some soil.

8:48. On as rocky material as possible but with considerable soil and silt. On schists of Palaeozoic Shuswap.

9:48. On slope where some soil has slumped from hillside complex. Close to Shuswap Fall. On Mesozoic diorite and quartz diorite. About 2 miles south of Okanagan Landing on East side of Okanagan Lake.

10:48. On rocky talus slope with little soil. On quartz diorite, about 5 miles south east of Salmon Arm.

11:48. On soil-covered sidehill underlain by Palaeozoic argillite and chert. South of Equeses Creek about 6 miles from north end of Okanagan Lake.

12:48. On soil-covered slopes underlain by granite. About half down Long Lake on west side, near "old" road.

13:48. On soil-covered ground probably underlain by Tertiary volcanic (andesite?). About 2 miles south east of Vernon.

14:48. On soil-covered ground underlain by tuffs and sediments of unknown age. From necessity of highest dam on N. fork of Watson Bar Creek. Originally believed on basis of much panning, to be well removed from any gold mineralization. Biogeochemical results cast doubt on the validity of the above belief but as yet no gold has been found in place and only negligible amounts of very fine gold have been panned. A scarcity of ourcrops indicates that it never should have been considered a "negative" area in spite of failures to find gold after much pitting and panning.

13:46. 150 feet east of East Fault and 150 feet north of footwall outcrop of Sullivan ore zone.

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RECENT ANALYSES FOR AGE BY LEAD RATIOS

REFERENCES CITED

By O. B. Muench

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Abstract

Analyses (1) and (2) of early Tertiary pitchblende from Gilpin County, Colorado; (3) of early Precambrian monazite from the Huron Claim near Winnipeg, Manitoba; (4) of a monazite from near Las Vegas, New Mexico; (5) of a euxenite from Trout Creek Pass, Colorado, are reported with lead age ratios as follows: (1) 0.0146; (2) 0.0167; (3) 0.257; (4) 0.106; (5) 0.059.

The first four were executed with the help of a grant from the Elizabeth Thompson Science Fund, and the proportion of isotopes in the lead have been determined by A. O. Nier. The fifth was helped by the Penrose Bequest of The Geological Society of America. Some of the figures given in this paper have already been incorporated in the Report of the Committee on the Measurement of Geologic Time (1940).

Introduction and Acknowledgments

Several pitchblendes and monazites were analyzed for age during the summer of 1939. During the summer of 1941, a similar analysis was made on a euxenite.

The two pitchblendes were from Gilpin County, and of early Tertiary origin. The first was from Wood's Mine, Central City, Colorado. A pitchblende from this neighborhood (Kirk Mine, Gilpin County, Colorado) had already been analyzed and reported by Friedrich Hecht and Edith Kroupa (1936). They obtained a lead-uranium ratio of 0.011 which corresponds to an age of about 80 million years.

The author expresses his thanks and appreciation for the financial assistance of the Elizabeth Thompson Science Fund of the American Academy of Arts and Science in making the first four determinations and of the Penrose Bequest of The Geological Society of America in the analysis of the euxenite. The generous use of the laboratories, chemicals, and other facilities of the University of Missouri, made available for this purpose through the courtesy of the University of Missouri and Dr. Allen E. Stern and the late Dr. H. E. French, Chairman and acting Chairman of the Department of Chemistry, is deeply appreciated. Much credit and thanks are due the late Dr. Alfred C. Lane for his constant help and inspiration during this work. The help of Dr. J. P. Marble in editing and suggesting certain corrections and changes in this paper is greatly appreciated.

Pitchblende from Wood's Mine, Central City, Colorado

General Discussion

The specimens used for this study were obtained by Dr. A. C. Lane from the Smithsonian Institution. The weight of the sample as received was 138 grams, and the mineral had a specific gravity of 7.50. The sample had a specimen number painted on it, so, in preparing the portion for analysis, care was taken not to include any of the painted portion, and thus to

lessen the chances of lead contamination from this source.

After small pieces had been taken from various parts of the specimen, a selected average portion of the sample was ground in an iron mortar and finally in an agate mortar to pass through a 100-mesh sieve; all necessary precautions were taken to avoid lead contamination. The reagents used were carefully examined for lead and purified when necessary. Extra precautions were observed as the lead after this analysis had to be suitable for isotopic determination.

Previous papers describe or give reference to the details of the methods used in this analysis (Muench, 1937). The sample dissolved readily in 1–1 nitric acid. Silica was then removed by several evaporations. The bulk of the lead was precipitated as the sulfate with recoveries of lead as sulfide from all filtrates and residues.

Impurities (chiefly iron oxide and silica in minute amounts) in the final precipitation after weighing were determined and corrections made. Each sample of $PbSO_4$ was then dissolved separately in ammonium acetate, filtered, the solution precipitated with hydrogen sulfide, and finally again converted to lead sulfate and sealed in glass tubes. This set of lead sulfates was prepared for Nier to be used by him for isotopic determination of the lead.

Results of Analyses

The lead was determined as the sulfate on 10-gram samples

Sample Wt. g.	Wt. $PbSO_4$	Per cent Pb
10.0009	0.1562	1.066
10.0006	0.1556	1.062
10.0007	0.1551	1.059
	Average	1.063

The uranium was weighed as the pyrophosphate. The rare earths and thorium were first removed as fluorides. Then the hydrofluoric acid was completely replaced by sulfuric. The operations involving hydrofluoric acid or fluorides were all carried out in platinum ware. The iron, lead, and other common metals were removed during the course of analysis as described in previous papers. The final pyrophosphate residue was carefully examined and corrected for traces of silica. Traces of iron, titanium, tantalum, columbium, and zirconium were determined in dilute sulfuric acid solution of this residue by precipitation with a cupferon solution and corrections made where necessary.

Sample Wt. g.	Weight $(UO_2)_2P_2O_7$	Per cent U
0.2029	0.2200	72.32
0.2004	0.2171	72.25
	Average	72.28

After the separation as the fluoride, the thorium was determined by the peroxide method (Muench, 1937).

	Per cent
Thorium	0.11
Loss on ignition	1.43
Loss at 110°C. for three hours	0.46

The specific gravity of the original sample as reported by A. C. Lane is 7.50.

The "lead–uranium ratio" from the above data is:

$$\frac{1.063}{72.28 + 0.36 \times .11} = 0.014_7$$

The age of this mineral calculated from the above data, using the logarithmic formula of Holmes (1931), is 111 million years.

$$\frac{log\,(U + 0.36Th + 1.155Pb) - log\,(U + 0.36Th)}{6.6 \times 10^{-5}}$$

$$= 111 \text{ million years.}$$

Pitchblende from Gilpin County, Colorado

The second pitchblende, from Russell Gulch, Gilpin County, Colorado, was supplied by R. F. Hammer and sent to the writer by A. C. Lane. Specimens of pitchblende from this locality have been analyzed by Fairchild, Lind, Hecht (Report of Committee on Measurement of Geologic Time, Division of Geology and Geography, National Research Council, 1935) and Hillebrand (1900). The same precautions were taken, and practically identical methods of analysis were used as on the Wood's Mine sample.

Thorium by the Peroxide Method

Sample	Wt. g.	ThO_2 g.	Per cent Th
1.	10.0000	0.0057	0.050
2.	10.0000	0.0062	0.054
3.	10.0000	0.0062	0.054
		Average	0.053% Th

Uranium

Sample	Wt. g.	$(UO_2)_2P_2O_7$ g.	Per cent U
1.	0.3028	0.1740	38.33
2.	0.3012	0.1729	38.28
3.	0.3030	0.1738	38.25
5.	0.3040	0.1745	38.28
		Average	38.28% U

Lead 10.0000 g. samples

Sample	$PbSO_4$ g.	Per cent Pb
1.	0.0948	0.647
2.	0.0937	0.640
	Average	0.643% Pb

Loss on ignition (heated for 2 hours)..... 12.33%
Loss at 110°C. for 3 hours..... 1.32%

The $PbSO_4$ from this sample was sent to Nier. The "lead–uranium ratio" from the above figures is 0.0167.

$$\frac{0.643}{38.28 + 0.36 \times 0.053} = 0.0167$$

Monazite from Huron Claim, Manitoba, Canada

General Discussion

The monazite from Huron Claim, Manitoba, Canada, supplied by the Royal Canadian Museum, Toronto, was concentrated by R. Botinelly under the supervision of E. S. Larsen; when received by the writer it was a carefully selected and clean sample. This sample, which weighed 4.39 grams, was ground in an agate mortar, and 3.2033 grams of the sample was taken through the entire analysis, since a larger quantity of the mineral was not available. Extra precautions were taken as to the purity of chemicals and the analytical operations in order to get as accurate and reliable results as possible and to avoid contamination.

Previous papers describe or give reference to the details of the methods used in this analysis (Muench, 1938). These methods were slightly modified in this analysis.

Results of Analyses

Weight of sample taken through all these determinations, 3.2033 g.
Lead as $PbSO_4$, 0.0716 g.—1.524 per cent Pb
Uranium as pyrophosphate, 0.0135 g.—0.28$_1$ per cent U
Thorium by the peroxide method, 0.5697 g.
ThO_2—15.63 per cent Th
Loss at 110°C for 3 hours, 0.10 per cent
Loss on ignition, 0.75 per cent

The "lead–uranium ratio" from the above data is 0.257.

$$\frac{1.524}{.281 + 0.36 \times 15.63} = 0.257$$

DeLury and Ellsworth (1931) made an age determination on a uraninite from this district and obtained a "lead–uranium ratio" of 0.260.

Monazite from near Las Vegas, New Mexico

The analysis of the second monazite, which came from near Bull Creek about 15 miles from Las Vegas, New Mexico, and was furnished by Leon Guy of Las Vegas, was carried out with methods of analysis practically identical with the Huron Claim monazite. For comments by A. C. Lane on this monazite see *Report of Committee on Measurement of Geologic Time, Division of Geology and Geography, National Research Council* (1940). Results of analysis:

Pb, 0.372 per cent
Th, 9.39 per cent
U, 0.122 per cent
Loss at 110°C. for 2 hours, 0.127 per cent
Loss on ignition, 0.99 per cent
"Lead-uranium ratio", 0.106

$$\frac{0.372}{0.122 + 0.36 \times 9.39} = 0.106$$

Euxenite from Trout Creek Pass, Colorado

During the summer of 1941, an analysis was made of a euxenite from Trout Creek Pass, Colorado, furnished by James Boyd, Colorado School of Mines, Golden, Colorado. The mineral was collected by J. W. Adams of Idaho Springs, Colorado, from the Trout Creek Pass region. The specific gravity as determined by Berman was 5.00. Wahl (1941) worked on this mineral and reported some indication of a fourth radioactive series.

The J. Lawrence Smith method as modified by Wells (1928) was used as a basis for the

analysis of this euxenite as the mineral was readily decomposed by hydrofluoric acid. The results of this analysis are:

Pb, 0.293 per cent
U, 3.41 per cent
Th, 4.25 per cent
From these figures the "lead-uranium ratio" is 0.059.

$$\frac{.293}{3.41 + 0.36 \times 4.25} = 0.059$$

All figures have been checked.

Total sulfur as SO_3	0.03 per cent
	0.03 per cent

One determination was by fusion of the sample with sodium carbonate and potassium nitrate, the other with a mixture of hydrochloric and nitric acids, to get the sulfur in solution and oxidized.

The alkali metals were determined (in per cent) according to Wells' (1928) method:

Total as chlorides	0.75 per cent
Na_2O	0.29 per cent
K_2O	0.12 per cent
CaO	1.82 per cent
MgO	0.13 per cent
Total rare earths and ThO_2	31.70 per cent
ThO_2	4.80 per cent
Total Cb, Ta, and Ti oxides	52.25 per cent
Cb_2O_5 and Ta_2O_5	21.05 per cent
TiO_2 by difference	31.20 per cent

The proportions of the isotopes of the lead have been determined by Nier *et al.* (1941) for the first four of these minerals. Nier's ages agree most nearly with those given here, for the case of the element of which there is greatest abundance, and its ratio to the total lead when isotopes have not been determined.

These "uncorrected lead ratios" are collected here as part of the complete record of operations carried out by various workers, using various techniques, to determine the absolute geologic age of these specimens as closely as possible. The values given by Nier are, in the light of our present knowledge, the most nearly correct. To complete the record, and to make the full data available to other students of these problems, it is felt desirable to put the chemical analyses in permanent form.

The complete analysis of the euxenite is as follows (in per cent)

0.55	SiO_2		
1.82	CaO		
0.13	MgO		
26.90	Rare Earths (0.18 $(La, Tb)_2O_3$)		
4.80	ThO_2		
4.03	U_3O_8		
21.05	Cb, Ta, oxides		
31.20	TiO_2		
3.54	Fe_2O_3		
.20	Al_2O_3		
3.00	Loss on Ignition		
.04	MnO	V	None
.30	PbO	Be	0.0
.03	SO_3	Sn	0.0
.29	Na_2O	Zr	0.0
.12	K_2O		
Total 98.00			

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Short Notes

COMMENTS ON THE TACONIC SEQUENCE IN PENNSYLVANIA

BY GEORGE W. STOSE

In preparing a geologic report on the Carlisle, Pennsylvania, quadrangle for the new series of areal maps to be published by the U. S. Geological Survey, I had an opportunity to restudy the shale, formerly mapped as Martinsburg, in the area that extends southwest from the main body of shale east of Harrisburg. This shale belt joins the main shale body north of Hummelstown and extends southwestward across the limestone lowland, passing through Steelton and New Cumberland and ending southwest of Shepherdstown (Fig. 1). In discussing the "Taconic sequence" in Pennsylvania (Stose, 1946), I stated that the shale of this belt had many of the earmarks of the shale of the "Taconic sequence," but for reasons stated it was tentatively retained in the Martinsburg shale.

Formation contacts are exposed in very few places in the region, and faults are inferred from relations of near-by outcrops. The shale in the Steelton belt is intensely folded and crushed; it is cut by well-developed cleavage which obliterated the bedding except where it contains distinct beds of quartzite; it is intricately penetrated by quartz stringers and is stained by iron rust. It therefore shows evidence of having been intensely compressed and probably thrust. The thin-layered limestone with shale partings (cement rock), which underlies the shale in places on its north border and crops out almost continuously on its south border, also is intensely folded, carbonaceous layers are slickensided and graphitic, and the rock is injected by many quartz stringers. This cement rock evidently experienced the same compression and movement as did the shale, and, if the shale was thrust, so was the underlying cement rock, and the argument (Stose, 1946, p. 683) in opposition to the thrusting of this mass of shale therefore has no valid application.

The north border of the shale in this belt has an irregular wavy outline, with salients and reentrants, such as a remnant of an eroded thrust plate might have. Also, the shale front transgresses the limestone formations to the northwest, as north of Steelton, where it overlaps a synclinal area of Stones River limestone, and southwest of Shepherdstown where it transgresses the boundaries of formations down to the Elbrook limestone. These unconformable relations of the shale to older formations were formerly regarded as evidence of stratigraphic overlap (Stose and Stose, 1939) before fault relations were suspected. This belt contains red and green shale and has associated hard quartzite beds, which is one of the characteristic features of the shale assigned to the "Taconic sequence" in the main belt. Such beds are not known in the shale recognized as Martinsburg. The red and green shale at the north border of the belt west of Hummelstown overlies cement rock at the border of the shale farther west, as do similar beds in the main shale belt. The apparent order of beds assigned to the "Taconic sequence" (Stose, 1946, p. 670–674) is as follows:

Taconic sequence in eastern Pennsylvania

Gray to black shale containing graptolites of Normanskill age
Red and green shale, and locally quartzite
Gray shale with scattered thin layers of limestone
Platy gray limestone with interbedded shale in the upper part and thin shale partings below.
Thick-bedded limestone and limestone conglomerate, containing in lower part glassy quartz grains and a few fossils.

The stratigraphic position of the shales that contain relatively large faunules of Norman-

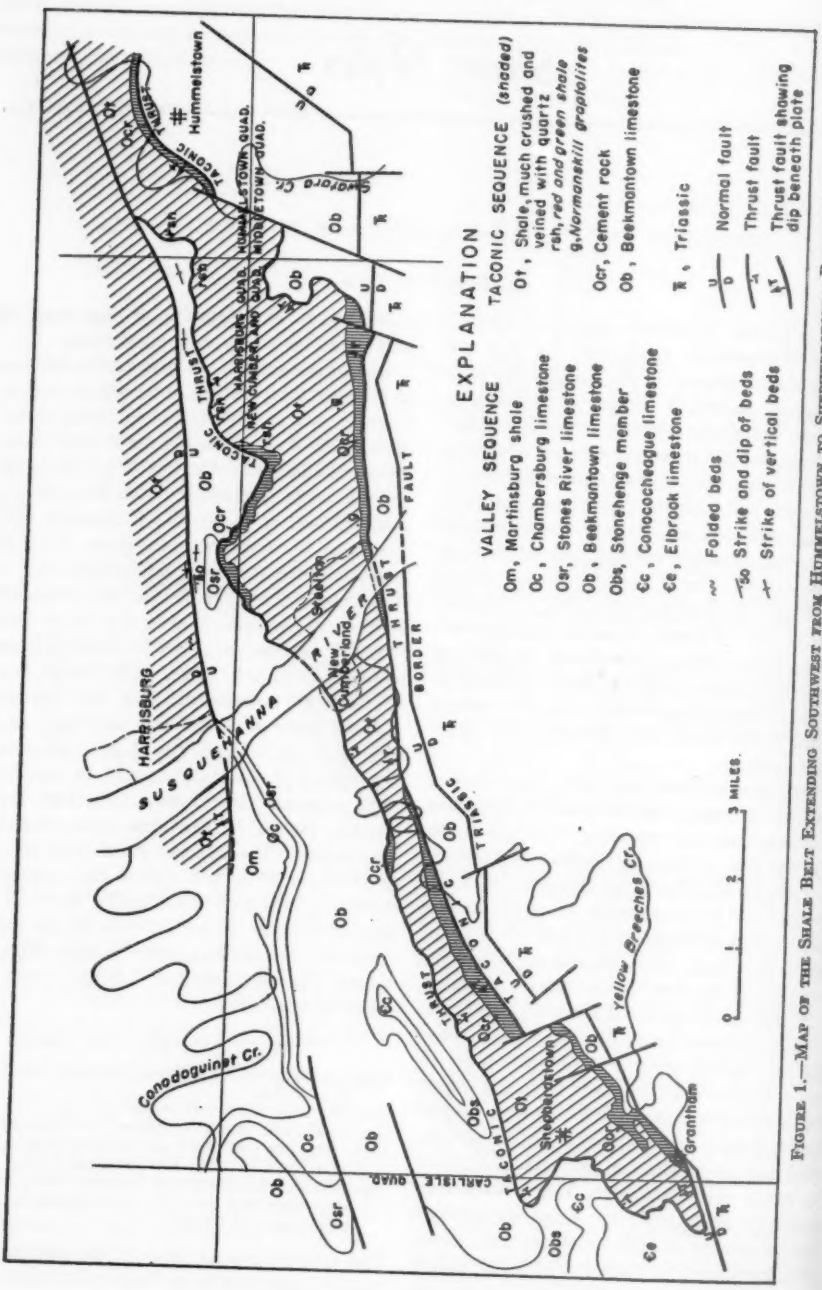

FIGURE 1.—MAP OF THE SHALE BELT EXTENDING SOUTHWEST FROM HUMMELSTOWN TO SHEPHERDSTOWN, PENNSYLVANIA

skill and Deepkill graptolites on the west bank of the Susquehanna River 5 miles north of Harrisburg (Stose, 1930, p. 639–641; Willard, 1943, p. 1097–1098), with reference to the red shale and the limestones near the base, is not precisely known.

Two well-exposed outcrops at the shale contact near the postulated "Taconic thrust" show such confused relations that interpretation is not clear. In a road cut at the south edge of Steelton, graptolites of Normanskill age were found in gray arkosic beds close to thin-bedded limestone containing other Ordovician fossils. Massive limestone and dolomite in the road cut appear to be thrust into the shale. Similar confused relations may be observed in a quarry west of Hummelstown, where Beekmantown limestone overlies slickensided shale. These confused relations may have been produced by resistant limestone beds in the thrust mass that penetrated and rode over the more yielding shale near the fault contact.

The south border of the main shale area east of Harrisburg (Fig. 1) is nearly straight, east-west, and the observed strikes in the adjacent Beekmantown limestone parallel this contact. The beds are vertical or dip steeply south. Although this contact is the south edge of the overthrust "Taconic sequence" in the main body of shale, its straight trend is in marked contrast to the wavy contact at the north border of the Steelton area just to the south, suggesting that the straight contact may be due to later vertical movement on a normal fault, related to Triassic faulting.

This evidence strongly favors the inclusion of the belt of shale that extends southwest from Hummelstown to Shepherdstown in the "Taconic sequence," and furnishes added proof of fault relations between the shale of the "Taconic sequence" and the adjacent limestones. The recognition of the Taconic sequence in Pennsylvania has cleared the stratigraphy of the Martinsburg shale by removing from it anomalous lithologic units and beds containing Normanskill and Deepkill graptolites. Further detailed study is needed to establish its limits and the presence elsewhere of fault relations.

FIGURE 1.—MAP OF THE SHALE BELT EXTENDING SOUTHWEST FROM HUMMELSTOWN TO SHEPHERDSTOWN, PENNSYLVANIA

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